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GEOGRAPHICAL DISTRIBUTION OF ORE DEPOSITS IN AUSTRALASIA.[1]

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INTRODUCTION.

THE accompanying brief note is an attempt to establish a rough grouping of the ore deposits in Australasia, and to show their broader relations with the geological structures associated with them. Brief reference is made also to the outlying islands such as New Zealand, Fiji, New Caledonia, the New Hebrides, the Solomons, New Guinea, Timor, and Java.

It has been considered advisable to approach the problem by a consideration of the geological history of the southwestern Pacific region as a whole, and to confront this knowledge in turn with the known distribution and the nature of the ore deposits in the great region under reference.

It is hoped thus to bring into prominence the relation of ore deposits to processes of folding, to the physical and chemical conditions of the abyssal laboratories of the earth's crust, and other related questions.

[1] Presented to the Society of Economic Geologists, Ann Arbor Meeting, December, 1922.

TOPOGRAPHY OF REGION.

The arrangement of the main topographical forms within Australia and the outlying islands is very similar to that of other continents which border the Pacific, namely, a sequence of land forms, as earth undulations or waves, from the continental nucleus to the Central Pacific, the prominence of the forms and relative youth of the activities being accentuated with progressive approach to the main ocean itself.

In the Australasian region this intensity of crustal undulation increases in a direct measure from southwestern Australia both to the north, the east, and the southeast. Thus southwestern Australia consists of a low compact plateau rising from a height of 1,000 feet on the seaward side to heights of several thousand feet on the north and northeast portions. This plateau is not broken by tectonic gaps.

The eastern side of Australia, from Thursday Island to a point 150 miles west of Melbourne, is formed of islands relatively narrower and higher than those of West Australia. These upland surfaces are of variable height, and they follow the coast for a distance of 3,000 miles. Their continuity is broken somewhat by the presence of numerous structural gaps representing differential elevations.

The vast intervening area, separating the plateaus of eastern and western Australia, may be divided roughly into two portions, namely, a western one, consisting of low-lying plains and shallow lake basins, diversified by long strips of high plateau which possess flexed and faulted margins. The orientation of these plateau strips or ranges is subparallel with that of the eastern and northeastern margins of the western Australian plateau. The eastern portion consists of low-lying plains of accumulation, such as the Great Artesian Basin of Australia (650,000 square miles) and the Riverina (70,000 square miles) and associated lowlands.

Beyond Australia, in arcs suggestive of the curve of Eastern Australia, lie the islands of Sumatra, Java, Borneo, Celebes, Gilolo, New Guinea, the Greater Solomons, the New Hebrides, New Caledonia, New Zealand, Fiji, Tonga, Society, and Paumotu,

groups separated by ocean depths. These all represent plateaus which, in the main, are narrower but higher than the highlands of Australia. The age of all the main lines is the same, and the stage of their dissection by stream action is almost identical.

All are plateaus with faulted and flexed margins. None are of the type usually understood as "fold mountains."

Each has had a complex history. In early Cenozoic time a series of similar forms, similarly situated, were produced. They were not topographical features of importance, however, such as are the plateaus of today. On the other hand, like the early Cenozoic types, they were of the nature of earth waves which had a vibratory and undulatory growth.

In the Middle Miocene, the land crests of the earlier Cenozoic had been denuded and the sub-horizontal surfaces developed therein had been re-elevated, the axes of uplift or undulation moving slightly from the continental nucleus.

In the closing Tertiary the mighty plateaus which adorn the Pacific region were formed as the algebraic sum of a series of vertical and vibratory movements of the denuded Miocene land crests. These movements were also of an undulatory nature.

The Pleistocene movement is similar to that of the Pliocene but is confined to areas much less in extent.[2]

It may be said thus that the Cenozoic movements have been rhythmic in space and time, the successive plateaus being expressive of the total sum of vibrations of opposite signs, all having also a lateral component, thus causing a movement of the main axes of the earth waves along radial lines drawn from the continental nuclei to the Pacific.

THE GEOLOGICAL HISTORY OF AUSTRALIA.

The locus of "folding" in Australia has moved progressively with the passage of time, from the southwest of Australia to the north and east, to the accompaniment of the gradual but interrupted filling of low-lying areas occupying the spaces

[2] Andrews, E. C., "Coral Reefs," Presidential Address Roy. Soc. N. S. W., May, 1922.

between the older rings or crests of growth. As an example, the Palæozoic folds might be expected to occur to the north and east, alike, of the great Archeozoic nucleus of West Australia and the subparallel belt of old rocks which occur within the Northern Territory, northwestern Queensland, South Australia, and Broken Hill.

Archeozoic.—The rocks which appear to be Archeozoic in age are arranged in two or more rings or zones in the southwestern Pacific. Thus southwestern Australia appears to have been the old nucleus of the continent. It is probable that another great belt or ring of Archeozoic rocks passes through the Northern Territory, Cloncurry, the eastern portion of South Australia, and Broken Hill. The islands of New Zealand, New Guinea, Borneo, Celebes, and the Sumatra line possess schists and types of gneiss which are assigned generally to the Archeozoic but which probably are of later age.

The rocks mentioned above are all crumpled in a high degree and appear to have been developed within the zone of flowage.

The description of Maitland[3] suggests that the great mass of the igneous rocks of western Australia, which intruded the Archeozoic sediments during periods of intense folding, are of the nature of sills. This is shown especially well in the various text-figures and maps illustrating his descriptions of mining fields.

"A most noticeable feature in these crystalline schists is constituted by these bands of cherts and brilliantly coloured jaspers. . . . The brilliant appearance of these jaspilites is due to interlamination of red, white and dark coloured bands. . . . These bands of jaspilites present a ribbon-like structure. . . . Some of these jaspilites are found in intimate association with the greenstone and altered schists, which suggests that the former may, in some cases, have originated as a replacement of basic lava flows or sills" (p. 13).

The general strike of the Archeozoic of the area under consideration is northwest to southeast, but the rocks, lying further east, appear to surround these in a measure, being west-north-

[3] Geol. of W. Australia, The Mining Handbook, Ch. I., Geol. Surv. W. Australia. 1919.

west in the Northern Territory, as for example the MacDonnell Ranges, and almost north and south in South Australia.

In speaking of the ancient Warrawoona series in the Pilbarra field he says:

"These older dike rocks are often rudely cleaved and foliated and seem to occur in intimate connection with, or parallel to, the principal structural lines of the district . . ." (p. 16).

"The Warrawoona beds are intruded by the large granite mass which occurs in the form of a huge batholith. . . . The granite presents a rude foliation or banding which is parallel to the general strike of the beds of the Warrawoona series" (p. 17).

These western Australian rocks are traversed by dolerite dikes of a much older period. Similar dikes are common within the Archeozoic of South Australia, and of Broken Hill.

The Northern Territory, South Australia, Cloncurry, and Broken Hill contain large exposures of similar rock types. In Broken Hill the igneous intrusives are sills, in the main, without visible feeding sources.[4]

The older schists of the outlying islands do not appear to have been studied in detail and no reliable record of their age has been obtained.

Within the low shield or nucleus of western Australia lie various types of post-Archean, but Pre-Cambrian, rocks, apparently altered and folded to a slight degree only. In a similar manner the so-called Pre-Cambrian tillite of Broken Hill has not suffered to a great extent from the agencies of folding and metamorphism. These later types, indeed, appear not to have been changed even to slates except at a few points where the basal beds have moved differentially with respect to the Archean basement upon and within which they rest.

Before these Proterozoic rocks were deposited upon the Archean nucleus and outer ring, the older rocks were denuded to an extent such that the zone of rock flowage was exposed over vast areas. This connotes the removal of a very great thickness of overlying rocks.

[4] Andrews, E. C., "Geology of Broken Hill," Memoirs Geol. Surv. N. S. W., No. 8, 1922.

Since that period these Archean areas have been in a condition, relatively, of stable equilibrium while the "Sturm und Drang" of mountain making has retreated progressively, in time sequence, both to the east and north.

The Cambrian, Ordovician, Silurian, and Devonian sediments appear to have been deposited both between the two Archeozoic belts and beyond the outer one to the east. These older Paleozoics have a magnificent development both in South Australia and in Tasmania. They occur, apparently, in the main island areas, such as New Zealand.

The close of the Ordovician appears to have been a great folding period, and one also of great metamorphism. In some localities, as at Forbes, in New South Wales, the Silurian overlies the Ordovician unconformably, the former being devoid of alteration beyond the formation of claystone, whereas the original shales of the Ordovician have been changed to slate, phyllite, mica schist, and gneiss.

The Permo-Carboniferous may be cited as an example of the instability of the Australian continent in point of time progressively from the southwest to the northeast. In western Australia they are not only gently inclined but in places they are only slightly compacted as recorded by David and Maitland. In Tasmania these rocks are arranged almost horizontally. In Victoria they are also without observable dip except at places where they have been affected by warping and faulting in late Cenozoic time at the margins of the highlands. In southeastern New South Wales sediments of this age are gently warped, but at the Hunter River, 100 miles north of Sydney, they are domed irregularly.[5] Northward of this area, along the coastal strip of the continent, they are folded closely in places.[6] At a distance of 200 miles from the coast the dip of these sediments is very slight.

No folding movement of note has taken place in Australia

[5] David, T. W. E., "Hunter River Coalfield," Memoirs Geol. Surv. N. S. W., No. 4, 1907.

[6] Andrews, E. C., "The Structural Relations of Australia," *Journal of Geology*, 1916.

since the Paleozoic, and no ore deposits[7] younger than the Paleozoic have been recorded from the continent.

The story of folding in the southwestern Pacific is carried a few chapters beyond the close of the Australian record, and the ages of these have been deciphered by a study of the fossils which have become involved in the folding of the rocks of these groups.

From this examination it would appear that there has been both a Mesozoic and a Cenozoic period of strong folding therein, the intensity of movement dying in a southerly direction considered from New Guinea as a datum.

At the close of the Tertiary the island arcs were raised on a magnificent scale to form the present land crests of New Guinea, New Zealand, and the associated island groups. As a set of subparallel land crests was formed in these groups, they tended to creep and to involve the beds of intermontane outwash gravels in the process. With the revival of uplift the axes of elevation moved slightly and thus some of the folded gravels of the erstwhile troughs were involved and became part and parcel of the plateau or land crest.

If the rocks of Archeozoic age in Australia be taken as a datum, and if the schists of the island rings be considered as belonging to a post-Archean period, then it would appear that the extremely old rocks of the southwest Pacific lie in belts which are approximately confocal, each with a general dip to the east and north, the western Australian types towards Queensland, the greater island area towards the Central Pacific, the latter widening the island festoons in directions from New Zealand to the Philippines via Fiji, and it would appear that western Australia had risen at various times, and had been tilted toward the Pacific

[7] By the term "ore deposits" as used in this note is implied those types which are usually known as the quartz or siliceous deposits containing copper, lead, gold, iron, tin, tungsten, and related metals, and which have been produced beneath the surface after the formation of the containing sediments themselves. Types of deposits such as coal seams, carbonate of iron beds, the "brassy tops" of coal seams, gold and tin placers, and related formations, are not included here.

by the depressive action of folding to the north and east, or by an undulatory movement, which was mainly up-and-down, and only in a slight manner translatory or creeping. This movement appears to have depressed the front of the mainland wave progressively with the passage of time.

This differential and progressive rising in vibratory and undulatory manner, that is, as crests of land waves, indicates the division of the continent into regions, the exposed rock systems of which, in turn, serve as rough indices to the variable chemical and physical conditions which characterized the ancient laboratories of the earth's crust, considered from the point of progressive depth.

From the brief description above of the growth of Australia, it might be expected that physical and chemical products of a similar nature have been formed at comparable depths.

Thus the present surface of southwestern Australia once existed within the core of the great Archeozoic mountains. Today it represents the portion of the continent which has been denuded in the greatest measure by sea and stream. It might be expected, therefore, that here would be exposed the "end products" of the actions set up within the deepest laboratory in Australia which has been made accessible to modern investigators.

The Camooweal, Cloncurry, Broken Hill and the South Australian areas of Archeozoic rocks might be expected to contain the "end products" formed within a laboratory of comparable but slightly less depth.

The older rocks of western Tasmania, of Victoria, and of southeastern New South Wales might be expected to contain the characteristic "end products" of a laboratory less deeply buried, while the rocks of coastal Australia, north of the Hunter River, might be expected to contain the "end products" of laboratories which are relatively shallow.

In this statement is implied the end results only of chemical and physical activities which were prominent during the period of powerful folding for the region concerned. The more superficial activities which affected the same regions during much

later time, after considerable denudation had taken place, are not considered here. For example, the closely folded rocks of the zone of flowage for the Archeozoic rocks in Australia were brought subsequently into the zone of fracture by the combined forces of elevation and denudation. At this stage numerous dikes of basic nature intruded the older rocks in great numbers. In a case such as this the igneous rocks and the ore deposits, which were formed within the zone of flowage, are alone considered.

In a similar way various "saddles" were formed within the apices of the folds in the slates of Bendigo and Ballarat within Victoria. These appear to be of the same age as the great folding period. Under similar, but less pronounced conditions, the "saddles" were intruded by basic dikes. The conditions under which the "saddles" were formed are those considered in this discussion and not those under which younger dikes intruded the sediments and "saddles" alike, unless the latter be specially indicated.

The island arcs might be expected to reveal a history somewhat similar to that of the Australian regions, but with a few additional, and more recent, chapters.

A splendid opportunity appears thus to be offered to apply this knowledge of the history of folding in Australia to the study of igneous rocks, and ore deposits, not only in Australia, but in all other continents.

This is an inference from the belief, on the one hand, that the ore deposits of the Australasian region were formed during periods of folding, and on the other, that the ore deposits are related, intimately, to igneous emanations.

If it should be found that the ore deposits of the more abyssal laboratories of the earth's crust present differences of a fundamental nature in regard to shape and composition as compared with those which have been formed nearer the surface of their time, some far-reaching and useful principle might thus be obtained, a principle applicable possibly to all continents, such as South America, North America, Europe, and Asia, which have ancient and extremely denuded nuclei, and from which the moun-

tains grew outwards towards the oceans, in pulses, or rings of undulations, and which may be either insular, as New Zealand, or syntactic, as the Andes, Sierra, Selkirks and Rockies of America.

DISTRIBUTION AND NATURE OF MAIN ORE DEPOSITS IN AUSTRALASIA.

Western Australia.

The literature of the ore deposits of western Australia is considerable, including the valuable reports by Blatchford, J. W. Gregory, Jutson, Larcombe, Maitland, McLaren, Pittman, Simpson, St. Smith, Woodward, and others. The accompanying brief notes are compiled and abstracted from Maitland's epitome.[8]

"The mineral deposits of Western Australia occur in areas generally as more or less parallel belts of relatively narrow lateral dimensions, though in certain localities they appear as small isolated areas or patches . . . narrow well-defined belts have a general northwest and southeast direction. . . . The ore deposits in these belts or zones . . . occur in relatively short lenticles arranged *en echelon*" (p. 44).

Northwest.—An immense lens of iron ore, apparently as a replacement in great measure, is reported from the ancient rocks of the northwest.

Pilbara.—Maitland divides the ore deposits of this great district into six main and distinct groups (p. 447).

(*a*) Lalla Rookh, about 30 to 40 miles in length.
(*b*) North Pole, Talga Talga, Bamboo, 50 miles in length.
(*c*) Marble Bar, Warrawoona, Yandicoogina, Mount Elsie, and Boodalyerri, 80 miles in length.
(*d*) Nullagine, Middle and Sandy Creek, 41 miles.
(*e*) Tambourah, and western Shaw, exceeds 30 miles in length.
(*f*) North Shaw, a few miles.

"The general direction of these auriferous belts almost everywhere coincides with the strike of the schists which, with one or two exceptions, invariably form the matrices of the gold-bearing reefs. The prevailing dip of the belts coincides with the general trend of the main structural features of the district" (p. 448).

[8] Maitland, A. G., "Ore Deposits of Western Australia." Federal Handbook, Brit. Assoc. Ad. Sci., Australasian Meeting, 1914.

In describing the minerals of the Pilbara, Maitland says:

(P. 448) "Quartz reefs occur in great abundance throughout the schistose rocks. . . . The quartz reefs are of two distinct types, namely, white quartz reefs and laminated quartz and jasper veins approaching very closely the hematite-bearing quartzites (?) which invariably form a conspicuous feature in most of the gold fields of the State. Some of the laminated quartz veins range from almost pure quartz, through banded jaspers, with crystals of magnetite, to bands appearing to the eye to be virtually pure hematite. The quartz reefs . . . invariably occur along the planes of foliation (? bedding) of the schists. . . ."

"The auriferous reefs cannot be said to possess great length, and are, as a rule, small, though they occasionally swell into large lenticular masses. Some of the reefs have been traced along the outcrop for distances exceeding 2,110 feet. . . ."

Ashburton and Gascoyne Gold Fields.

(P. 450) "The most important feature" (of this field) "is the saddle reef nature of the quartz veins, which bear a striking resemblance to those of Bendigo in Victoria."

Speaking of the great Kalgoorlie Gold Field (p. 453):

"The rocks of Kalgoorlie and Boulder consist of (*a*) ancient sedimentary rocks . . . , (*b*) older greenstones (calc schist and lne-grained amphibolites), (*c*) newer greenstones (quartz-diabase and coarse-grained amphibolite), (*d*) peridotites, (*e*) porphyries, and (*f*) quartz and feldspar porphyries."

The sedimentary rocks have a general trend to the north-northwest, and an average dip of 80 degrees to the west. The quartz-diabase appears to contain the principal gold-bearing deposits known at present.

"The ore deposits of the field form relatively narrow bands, trending generally northwest and southeast. Many of the ore lenses are of great length. . . . The principal lode minerals in addition to gold and tellurides . . . are iron pyrites, marcasite, chalcopyrite, tennantite, asbolite, carbonates of iron, lime and magnesia, sulphates of lime and magnesia, hematite, magnetite, ilmenite, . . . tourmaline, chlorite, albite, rutile. . . . Iron pyrites is the most important mineral after gold and tellurides" (p. 454).

Copper.—The western Pilbara Field is the most important in the state and is selected as the type.

"The ore deposit is a very flat-lying lode, conforming to the bedding of the enclosing schist country, which has a general strike of northwest and southeast" (p. 405).

Tin.—Although western Australia and Northern Territory are preëminently countries containing acid granites, such as are associated commonly with tin fields elsewhere, nevertheless the tin, tungsten, molybdenite, and bismuth yield of western Australia is almost negligible in importance. The explanation of this feature is supplied below.

Northern Territory, South Australia, Northwest Queensland, New South Wales West of the Darling River, and Possibly Part of the West Coast of Tasmania.

Northern Territory.—From Maitland's[9] description it would appear that the main ore deposits of this region are lenses and replacements of gold ore along bedding planes. Of these, Arltunga may be taken as the type. The ore deposits of the district have a very gentle dip conforming to the bedding planes of the enclosing schists.

Northwest Queensland, Cloncurry.—The rocks containing the ore deposits of Cloncurry[10] are ancient schists intruded by granite, diorite, and other igneous types.

The ore occurs as lenticular masses interstratified with sediments. Some of the individual occurrences are very large. Lenticular masses of hematite occur on the tops of the local ridges.

South Australia.—The prevailing rock types containing the main ore deposits of this great region appear to be Archeozoic schists invaded by large sills. These older rocks are overlain in places with tillite which is either Lower Cambrian, or Pre-Cambrian, in age. The latter are intruded neither by the granites nor by the other intrusives of the underlying Archeozoic.

The principal ore deposits are the immense iron deposits of the Iron Knob district, and the Wallaroo-Moonta copper lodes.

[9] *Op. cit.*, p. 456.

[10] Pittman, E. F., "Mining Fields of Eastern Australia." Federal Handbook, Brit. Assoc. Ad. Sci., 1914, Australasian Meeting.

With these may be included the old and famous Burra Burra lode.

Iron Knob and Iron Monarch.—These immense deposits of hematite appear to be replacements[11] in places, and also pressure lenses and injections in part, during the first great folding of the Archeozoic.

Wallaroo-Moonta.[12]—The rocks in which the deposits occur are Pre-Cambrian and apparently Archeozoic. Upon these lie sediments which are the equivalents of the tillites believed to be Lower Cambrian by Howchin,[13] but Pre-Cambrian by some other geologists. The sediments consist of:

"Quartzite, quartzite schist, mica, hornblende, actinolite schists, phyllite, slate and intensely altered limestone" (p. 20).

With them are associated:

"basic igneous rocks, felsite and feldspathic porphyry and later, but still Pre-Cambrian, granite and pegmatite intrusions" (p. 20).

The known productive lodes of Moonta are wholly confined to a large intrusive mass of feldspar porphyry. The granite (p. 29) is described as a mass having an aureole, penetrated by granite, pegmatite, and aplite, dikes.

Minerals of Moonta and Wallaroo.—According to Jack (pp. 46–47) these important lodes consist of pegmatite dikes, the Moonta being more like typical pegmatite dikes, the Wallaroo representing deposits from the parent body.

Moonta Minerals.—Microcline feldspar, schorl, hematite . . . biotite, apatite and fluorite. A little molybdenite is present also.

"The Wallaroo mineral assemblage is on the whole rather more varied than at Moonta. The gangue minerals consist of quartz, coarse flakes of biotite . . . a little feldspar, schorl, apatite, fluorite, amphibole, pyroxene, siderite, calcite, dolomite, rhodonite, chlorite, muscovite, and sericite are also present in small amount. Other minerals are chalcopyrite, pyrite, pyrrhotite, and small amounts of galena, blende, ferberite, scheelite, molybdenite and gold."

[11] Jack, R. L., "Iron in Resources of South Australia," Bulletin No. 9, Geological Survey South Australia, 1922.

[12] Jack, R. Lockhart, Geol. Surv. S. A., Bull. No. 6, 1917.

[13] Howchin, W., "Geology of South Australia." Gov. Printer. Adelaide. 1917.

Burra Burra.—This mine has been abandoned. From descriptions it appears to have been a huge lens, mainly of replacement and pressure growths in the ancient rocks associated with it.

No tin, tungsten, bismuth, or molybdenite deposits of commercial value have been recorded from South Australia. On the other hand, minerals such as apatite, radio-active minerals, and graphite are not uncommon in these ancient sediments.

Broken Hill District.[14]—The main Broken Hill lode contains galena, together with zinc-blende, silver, and a small proportion of copper and pyrite.

The prevailing rock types of sedimentary origin appear to have been silts and shales of Archeozoic age, but which have been intensely and closely folded and altered to sillimanite and mica gneiss. The ore deposits exposed at the surface have been developed almost entirely within the zone of rock flowage.

These old sediments were intruded by numbers of sills composed of augen gneiss of primary type, aplite, norite (amphibolite), and pegmatites of replacement as well as pressure lenses and of injection. Of these the pegmatite and the amphibolite intrude the various igneous gneisses, whereas the pegmatites intrude both gneisses and amphibolites.

These sills pre-dated the folding. The metamorphism of the Archeozoic types was differential, the more intense action being local. A subcircular area, 20 miles in diameter, of sillimanite gneiss, with garnet, feldspar, and biotite, occupies the center of the fold. These sillimanite gneisses were folded with the sills and were injected with innumerable lenses, "eyes," and patches of pegmatite.

Outside this area of sillimanite gneiss lie sandstone, and altered limestones, together with great thicknesses of andalusite, chiastolite, and mica-schist, all of the same age as the sillimanite gneiss, thus representing a decreasing intensity of metamorphism with progressive distance from the center. On the west side of the sillimanite area a great number of granite sills occur from which small tongues or apophyses project into the surrounding schists.

[14] Andrews, E. C., *op. cit.*

On the eastern side of the sillimanite area occur sills and tongues of serpentine containing the platinoid minerals.

The main Broken Hill rocks are disposed in discontinuous arcs or curves within the sillimanite area. The ores are galena, silver, and zinc blende. The gangue is rhodonite, manganese, garnet, gahnite (zinc spinel), aplite, fluorspar, calcite, pegmatite with green feldspar, and quartzite.

The main lode is in the nature of a replacement of a great drag fold, attached to a zone of strain within which pressure lenses of ore are developed. In the area of the sillimanite schists, other similar, but much smaller, lodes occur, but without rhodonite. Outside the sillimanite area the galena lodes contain no zinc and, moreover, they have a gangue of carbonate of iron. These are associated with granite sills, which are absent from the sillimanite area.

Beyond this zone of rhodonite, garnet, galena, and zinc, together with the subparallel group of the galena with iron carbonate, lie the lenses of griesen containing tin and tungsten, which are arranged as offsetting lenses in discontinuous and outer arcs in altered slates. The latter lie 14 to 50 miles distant from Broken Hill in a northerly and northwesterly direction.

Within the sillimanite area again the main Broken Hill lode is paralleled by narrow lodes of magnetite intimately associated with quartz and garnet of the manganese type, but all in granular form. Outside the sillimanite area the magnetite is much coarser in texture and has little or no trace of garnet.

Erratics of this magnetite occur in the overlying tillite of Pre-Cambrian age.

Tasmania, Victoria, and Eastern New South Wales (South of Hunter River).

If the area west of the river Darling be excluded, this is a complete province and is characterized by the development of ore deposits of closing-Ordovician age together with Silurian and Devonian types. The deposits belonging to each of these great divisions show characteristic features.

They have been developed in a zone of combined fracture and flowage, but one in which the flowage phenomena are not pronounced. They are distinct from the deposits of the western area in which the phenomena of rock flowage are very marked.

Tasmania.[15]—The literature of Tasmanian ore deposits has been enriched by the work of J. W. Gregory, Loftus Hills, Twelvetrees, Waller, L. K. Ward, and others.

The Read-Rosebery ore deposits consist of silver-lead, zinc, and copper. They are, apparently, huge replacements of Paleozoic rocks in the form of lenses, the replacements taking the form of pyritic types of fine texture.

Mt. Lyell.—This famous deposit consists of great lenses of chalcopyrite and other sulphides in the form of replacements at the junction of ancient schist with conglomerates.

Blythe River Iron Ore.—This consists of a great vertical bed, or lens, of hematite apparently interbedded with slate and sandstone.

The types above appear to be Pre-Silurian and may be considerably older.

Later Tasmanian Deposits.—These consist of numerous and rich accumulations of tin which appear to have been formed at the close of the Devonian. The tin is associated with bosses and dikes of siliceous granite, whereas the tin of Broken Hill, and other western provinces, is contained within lenses of griesen.

The tin deposits of Tasmania appear to have been formed in the zone of fracture, and under a cover of rocks which had a thickness much less than those beneath which the great lenses of the West Coast mountains were formed.

Victoria.—This state is preëminently a gold region, partly as the result of deposition, mainly by replacement within the "kindly slates" of the Ordovician. The yield of gold exceeds £300,000,000 ($1,458,000,000) in value, of which the leads, or placers, have yielded £150,000,000 ($729,000,000), whereas the saddle reefs of Bendigo have yielded £80,000,000 ($389,000,000).

[15] Abstract from E. F. Pittman, Federal Handbook, Brit. Assoc. Adv. Sci., Australian Meeting, 1914, p. 416.

The periods of ore deposition appear to be at least closing-Ordovician, and post-Devonian. It is possible that closing-Silurian was a period of ore deposition also.

The literature is enriched by the work of Baragwanath, Dunn, J. W. Gregory, Herman, Junner, Murray, Richards, Selwyn, Skeats, Stillwell, and Whitelaw. The accompanying notes are based upon Herman's brief account.[16]

Ordovician.—The slates of the Ordovician are, preëminently, the repositories for the great "saddle" reefs of Victoria. These "saddles" appear to be replacements,[17] as is the case also at Mt. Boppy in New South Wales.[18]

They appear also to partake of the nature of igneous emanations but are not related to any visible igneous masses. Basic dikes are common in the "saddle" districts by they are stated to be younger than the "saddles" themselves.

Silurian.—Other fields, such as Walhalla and Woods' Point, are within folded rocks, but they do not appear to possess "saddles." On the other hand, they are noted for their occurrence as veins and as quartzite lenses, which are intimately related to, and apparently dependent upon, the presence of basic dikes somewhat similar to those which intersect the "saddles" of the Ordovician rocks. In the Ordovician country, "saddles" may be associated commonly with cross reefs, or fissure veins may be the dominant forms as in Ballarat east and Daylesford. These observations suggest that there has been more than one period of ore deposition in the Victorian gold fields.

Tin and tungsten occur sparingly in Victoria. This appears to be due to the absence of aplite and greisen from the slate regions.

New South Wales.—The ore deposits of central and southern New South Wales appear to belong to two periods at least, namely, the Ordovician and the closing-Devonian. The "sad-

[16] Herman, H., Brit. Assoc. Advan. Sci., Federal Handbook, Australia, 1914.

[17] Stillwell, F. L., "Gold Deposition in the Bendigo Goldfield," Bull. No. 4, Advisory Council of Science and Industry, Commonwealth of Australia.

[18] Andrews, E. C., Report on Canbelego Gold Field, Mineral Resources, No. 18, Geol. Surv. N. S. W., 1913.

dles" and the ore lenses of replacement and of pressure occur in Ordovician slates and schists, whereas the veins, the "contacts," and the "pipes" occur in Devonian rocks, which show slight traces only of metamorphism. Fine examples of the "pressure" lenses and of the "saddles," together with lenses of replacement, occur within the Boppy, Cadia, Cobar, Forbes, Hill End, Mt. Hope, and other mineral fields.

The ore types of subsequent age to those belonging to the Ordovician include certain gold fields, together with important deposits of tin, tungsten, molybdenum, and bismuth. The geological structures associated with these deposits suggest that the latter were formed very much nearer to the surface of the earth at that period than the lenses and "saddles" of the Ordovician.

The gold of the closing-Devonian is in veins. The tin and associated minerals, such as molbdenite, tungsten, and bismuth, are associated with the usual pegmatite, greisen, aplite dikes, and quartzite veins, and patches, all arranged round the margins of siliceous granites which intrude Devonian sediments.

Whipstick[19] and Yetholme may be taken as examples. In each case the sediments intruded by the siliceous granite bosses are Devonian in age, but are unconformably overlain by the lowest Permo-Carboniferous. These granite masses had flattish roofs.

The molybdenum and bismuth of Whipstick occur in "pipes" which are of granite, containing abundant manganese-garnet. The "pipes," as individuals, are discontinuous, but their molybdenite, bismuth, and garnet contents appear to have had access from one pipe to the other, although little or no trace of the passage between these points has been left in the intervening granite.

The molybdenite of Yetholme consists of a "contact" deposit in the form of a huge tongue or wedge which passes, or merges, insensibly from the granite and occupies a position between beds of quartz-porphyry and claystone. The gangue is

[19] Andrews, E. C., "Molybdenite," Mineral Resources, No. 24, Geol. Surv. New South Wales, 1916.

garnet, blebs of blue quartz, wollastonite, together with spheroids of calcite, the latter being developed in the claystone beds without visible feeding sources.

Plateau and Coastal Regions of Eastern Australia (North of the Hunter River).

The deposits of ore contained in this long meridional strip of territory occur as veins, "contacts," "pipes," and sporadic patches, and impregnations, within Permo-Carboniferous sediments in the main. A few inliers of Carboniferous and older rocks occur and in these the ore deposits appear to conform more to the types which are characteristic of the deeply-seated regions of the crust.

The deposits of the Permo-Carboniferous are associated, characteristically, with igneous rocks, such as basic dikes, in the case of the copper, lead, silver, and gold deposits, and as siliceous granites in the case of the tin, tungsten, molybdenum, and bismuth deposits. The veins cut both across the strike and the dip of the sediments.

Examples.—Charters Towers, Gympie, Hillgrove, Mt. Morgan, the tin-wolfram, and the molybdenite-bismuth deposits.

These, together with the other important fields of the district, have been described in detail in the excellent reports of Ball, Cameron, Dunstan, Jack, Rand, Jensen, J. H. Reid, St. Smith, and others.

Charter Towers.[20]—Here are gold veins in quartz mainly in granite traversed by dikes. They are almost invariably in proximity to these igneous dikes.

Gympie.—The ore deposits are in Permo-Carboniferous rocks.

An excellent set of maps illustrating the geology of the Gympie area has been prepared by B. Dunstan, and published by the Geological Survey of Queensland.

The ore deposits consist of lodes containing gold within black slate or shale. The beds of these sediments have a general dip to the east at an angle approximately of 25 degrees while the

[20] Reid, J. H., Report Charters Towers Gold Field, Geol. Surv. Queensland.

inclination of the reefs themselves is mainly to the westward at an angle approximating to 60 degrees. The vertical reefs have a western dip and the intersecting black or graphitic slate beds dip to the east.

Hillgrove, Drake, Rivertree.—These are fissure veins developed mainly within Permo-Carboniferous claystone and contain gold, copper and gold, and silver, respectively. The Hillgrove deposits, however, may be contained within an older Paleozoic inlier of slate.

Mt. Morgan.[21]—The ore deposits appear to be contained within Carboniferous rocks. The deposit is described as a mass of pyrite with admixture of copper. It is of the shape of a wedge 1,200 feet in length, 500 feet in width, and approximately 1,100 feet in depth. It occurs at the junction of two sedimentary formations. The deposit is traversed by basic dikes.

Tin-Wolfram and Molybdenite-Bismuth Deposits.—These, according to Andrews, Ball, St. Smith, and others, occur within Permo-Carboniferous sediments and appear to have igneous associations almost identical with those of the tin and molybdenite deposits of southern New South Wales and Tasmania. The age of the latter, however, is decidedly older than those of the Queensland and New England types, but both appear to have been formed under similar conditions of heat and pressure.

Ore Deposits of the Island Arcs.

From the island arcs long belts of schist have been recorded. At first sight these appear to be of Archeozoic age, but it is probable that, in many instances at least, they are much younger.

Gold and copper deposits occur within the folded areas of these island arcs, but many of the deposits are much younger than those of the continent. For example, the oil belts are traceable in rocks whose age is middle Cenozoic, whereas the ore deposits of southwestern Australia are almost wholly Pre-Cambrian and the latest deposits, even of northeastern Australia, belong to the closing Permo-Carboniferous.

[21] Pittman, E. F., Federal Handbook, Brit. Assoc. Adv. Sci. Aust., 1914.

The oil pools appear to occur in the crests of the earth waves forming the islands, and these oil deposits would appear to decrease in commercial importance in a most marked manner traced from the Asiatic to the Australian province, that is, traced southwest and southeast of northwestern New Guinea.

The crests of the land waves of the continent, that is, the plateaus corresponding to the folds containing the oil arcs of the islands, are comparatively gentle, and there is a correspondingly small percentage of oil to be expected from these continental areas of negligible folding in Cenozoic time within Australia itself, especially outside the northern and eastern margins.

SUMMARY AND CONCLUSIONS.

The ore deposits of Australia assume forms and mineral composition which are appropriate to the depths below the ancient surfaces at which they were formed.

Certain minerals, however, appear to be common to zones of all depths examined. Thus gold, silver, platinoid metals, and the sulphides of lead, zinc, iron, and copper appear to have been deposited at all depths. There is a tendency, however, for lead, zinc, and copper minerals to favor zones a little above the lowest portions of the crust which have been exposed by denudation. Deposits of magnetite and hematite occur as lenses and sills, at the greatest depths mainly as replacements of sediments, but in part also as pressure growths. These are characteristic of the lower portions of the ore zones, namely, those near, or within, the zone of rock flowage.

In the latter zone silicification is a common accompaniment to the ore entries, especially in connection with iron ores. This, at least, is the case with Australian types. The silica is suggestive of the pegmatite type and as a general "sweating through" and replacement agency from the deeper zone of rock flowage. No sign of the source nor passage of this silica is to be seen.

Tinstone, wolfram, molybdenite, and bismuth are characteristic of the regions nearer the surface existing at the time of their formation. They are associated with the closing phases of in-

trusions of siliceous granite, and they appear to have escaped from the lower zones of such intrusions and to have been deposited within, or near, the margins of the granite bosses, the latter being formed in portions of the earth's crust much nearer the surface than the zone of flowage within which the sills were developed. The aplite, pegmatite, greisen, and the quartz veins within and with which the wolfram may occur, are not of the sill type. On the contrary, they favor especially the cross dikes of segregation type and intrusive types.

Quartz fissure veins with gold, copper, silver, lead, and zinc, have been formed within portions of the earth's crust somewhat nearer the surface. They may occur associated with "saddles" of replacement, with beds of phacolite form, with great "pressure lenses" and with replacements of sediments, but in each case examined the veins appear to have belonged to a period of ore deposition which was much later than that which produced the associated "saddle." The Boppy "saddle," the Mt. Lyell and Read-Rosebery lenses of replacement, the "saddles" of Bendigo, Ballarat, Castlemaine, Forbes, Hill End, and Hargreaves, as also all their associated pressure lenses of silica, together with the Broken Hill "pressure lenses" of pegmatite, garnet, silica and sulphide, and replacements of the "drag folds," form a very instructive series.

The "pressure lenses" appear to have been formed between bedding planes, there being no trace of the passage of the ore emanations within the space separating individual lenses, although all apparently have been fed from the one source.

The great lenses of replacement have been formed at the junction of rocks of varying types and the replacement has progressed so wonderfully as to preserve within those rocks the traces of their innumerable and closely-spaced bedding planes.

The great ore deposits of the "drag fold" and the "close-fold" type, such as those of Broken Hill, represent replacements within the apices of sharp folds by the trapping therein of ascending emanations. In the "drag fold" proper, the replacement nature of the deposits is clearly shown and, as with the "saddles,"

these replacements are mainly within ancient slates or their equivalents, namely, sillimanite schist or gneiss. The "drag folds" proper are associated characteristically with steeply-dipping zones of strain containing ore and gangue in the form of "pressure lenses."

Especially illuminating in this connection is the case of the pegmatite replacement and injections within the Broken Hill area. In places therein rock masses of great volume appear to have been replaced by pegmatite, and associated with them also are large "pressure lenses." The Broken Hill lode itself appears to have begun in part as a replacement and injection by pegmatite.

The nature of "contact" deposits has prepared the student for the appreciation of the apparent penetration of sediments by ore emanations of igneous origin without leaving traces of their passage through these sediments. In the case of the "saddle," the Broken Hill deposits, the great magnetite and hematite lenses of Australia, the Cobar, Mt. Lyell, and other lenses of replacement, there is no sign of igneous rock which might be expected to act as a feeder for the rising emanations, whereas, in the case of the contacts, the original source of the emanations, which form the ore deposits, is suggested by the presence of igneous rocks in intimate association with the deposits themselves. The main point to be considered in these cases is the relative depth at which each has been formed.

A study of Australian geology indicates strongly that igneous rocks of intrusive nature tend to assume the form either of sills, or of flat lenses between the planes of bedding or of schistosity, and this tendency appears to be in proportion to the pressure and heat obtaining at the localities where the intrusions occur. Zones containing the lenses or sills, at great depth, that is, under great pressure, are persistent and follow the bedding planes, but as individual lenses they are discontinuous and show no sign of feeders or dikes arranged transversely to the strike of the associated sediments. It is certain at least that the mapping of the Broken Hill rocks shows the oldest igneous rocks there to be sills and lenses without sign of feeders along zones other than

the planes of bedding or schistosity which is almost coincident with bedding. A study of the Broken Hill area suggests also that isoclinal and shallow folding is typical of the zone of flowage in that region.

In proportion to the progressive proximity of igneous intrusions to the earth's surface of the period during which the igneous intrusions occur, there is a tendency for such intrusions to form bosses and batholiths with flattish roofs, together with a strong tendency to break across the bedding planes of the enclosing sediments. Pegmatite, aplite, and basic dikes of the cross type are characteristic of this zone of fracture.

The ore deposits considered in this note appear to be variants merely of igneous rocks. In the zone of flowage the ore deposit has the appearance of an igneous rock, but its feeding source is not apparent. In the zone of fracture the igneous nature of the ore deposit is much less pronounced than in the zone of flowage, but the igneous source of supply is indicated commonly by the intimate association of stock, boss, dike, or other igneous rock types.

The igneous rocks may be considered to be plastic, or solid even, at a certain depth beneath the surface of the earth in a specified locality. In this condition they have a mineral composition which may be different from that indicated by the sills, bosses, and dikes which arise from them at a later stage. Under conditions of great pressure, during periods of folding, opportunities for escape from such pressure, in certain directions, may be presented and emanations are thus discharged from the rock mass which may be plastic owing to the great differential pressure. These work their way through the zone of flowage and form pressure lenses and sills between bedding planes, and planes also of schistosity in places. The study of "contact" deposits, of "saddles," replacement lenses, pegmatite injections, and similar types, assists materially in this connection. Thus the tin, wolfram, molybdenite, and bismuth "pipes" of eastern Australia, the garnet pipes, the Broken Hill lode, the Australian "saddles," as also the great lenses of replacement, are shut off from apparent feeding source.

The study of the great lenses of magnetite and hematite in Australia, such as those of Yampa, Cadia, Iron Knob, and the Blythe River, tends also to the convergence of light on the problem. These show no sign of lateral segregation, and they appear devoid of all direct source of supply.

The pegmatites and granites of the zone of flowage show a gradual invasion and absorption, or replacement, of the sediments so invaded, as though they had "sweated" through the lower layers, and as though, under conditions of less pressure at higher levels, that is, those under the surface of the period, they had "injected" the sediments, and formed thereby pressure lenses and sills which tended to penetrate the surrounding sediments by the method of absorption and replacement. Nearer the surface the granites passed from the true sill stage to sills with accompanying tongues or apophyses.

Subsequently, and following the profound denudation of the area, true dikes of igneous material were formed in the same zones which at one stage had been deeply seated. In the latter the force of compression appears to have been the main controlling agency, whereas, in the case of the shallower forms, namely, the cross dikes and the bosses, the force of tension appears to have been more pronounced than that of compression.

GEOLOGICAL SURVEY,
SYDNEY, AUSTRALIA.

DETERMINATION OF DIP AND STRIKE FROM ANY TWO COMPONENTS, AND THE INVERSE PROBLEM.

D. F. HIGGINS.

It is proposed to give in this paper in some detail a discussion of the problem mentioned in the title, involving three distinct methods of solution: (1) A general solution by the methods of descriptive geometry, requiring only the simplest drawing implements; (2) the general mathematical solution, simplified, but complete; (3) a set of diagrams constructed from the formulas derived in (2) for the solution of the problems in any case likely to arise in any type of field work.

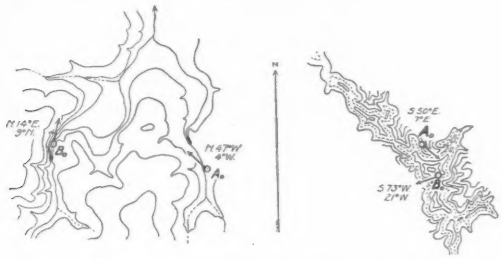
To define the problem more precisely: It is to determine the direction of strike and the amount of true, or maximum, dip from two of their measured components; and to determine the dip in a given direction or the direction of a given dip when the true dip and the strike are known. In this paper the less and greater angular dip components will be represented by α and β respectively, the less and greater gradient dip components by A and B respectively, the angle between the directions of the dip components by θ, the true angular dip by δ, the true gradient dip by Δ, the angle between the direction of strike and the direction of the lesser dip component (α or A) by ϕ.

THE METHOD BY DESCRIPTIVE GEOMETRY.

Often these observations are made in two intersecting valleys, as shown in Fig. 1. Again, they may be made along a ridge, perhaps as in Fig. 2. It must of course be assumed that there is no appreciable difference in true dip and strike between the two stations **A** and **B**,—the field observer must be sure of this.

The method of descriptive geometry reflects the conditions in the field. It is direct, perfectly general in its application, simple—

if one but takes the trouble to master the simple three-dimension concept involved,—accurate; and it leaves the derivation in a form suitable for filing and checking.



FIGS. 1 and 2. Common topographic conditions where components of dip and strike are measured—Fig. 1, in intersecting valleys; Fig. 2, along a ridge in the heads of ravines near its crest.

Let us consider the typical cases of Figs. 1 and 2. We must assume that the variation in dip and strike between the stations **A** and **B** is not enough to affect the solution unduly; then we may take it for convenience that the field measurements were made at the same stratigraphic horizon, if indeed they were not, for the stations are usually not far apart stratigraphically, and that this horizon is a plane within the limits concerned. We may then forget the topography and any part of the strata which have been removed by erosion, and we may construct for the moment the space diagrams of Figs. 3 and 4 to replace Figs. 1 and 2.[1]

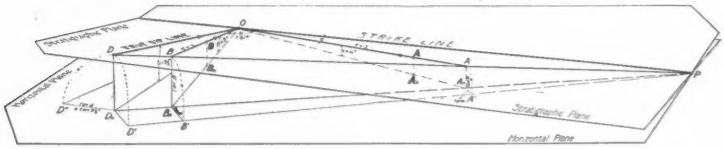


FIG. 3. Space diagram to illustrate the field conditions of Fig. 1, looking from the south. See top view, orthographic projection, in Fig. 5.

[1] It should be noted that the descriptive geometry necessary in accurately drawing these space diagrams is very much greater than that necessary in solving the problem in hand.

Since the straight lines whose dips and directions were measured at **A** and **B** are assumed to be in the same stratigraphic plane, they determine that plane, and they meet at some point, *O*,

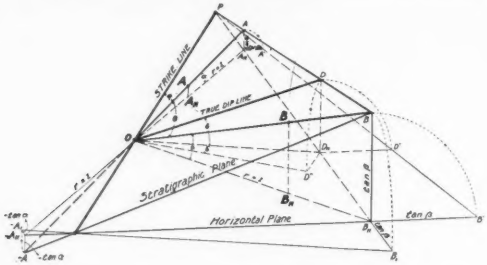


FIG. 4. Space diagram to illustrate the field conditions of Fig. 2, looking from the east.

in that plane.[2] Let a horizontal plane pass through *O* and vertical planes through the lines *O***A** and *O***B**. The perpendiculars from **A** and **B** onto the horizontal plane lie in these vertical planes. Call the feet of these perpendiculars $\mathbf{A}_H$ and $\mathbf{B}_H$. Then the angles $\mathbf{A}O\mathbf{A}_H$ (or α) and $\mathbf{B}O\mathbf{B}_H$ (or β) are the angles of dip observed in the field; and the angle $\mathbf{A}_H O\mathbf{B}_H$ (or θ) is the angle between the directions of dip as measured in the field.

Since these angular values do not change wherever **A** and **B** may be located on the lines *O***A** and *O***B**, we may choose these points so that $O\mathbf{A}_H$ and $O\mathbf{B}_H$ are equal, say OA_H equal to OB_H, with *A* and *B* on *O***A** and *O***B** vertically above A_H and B_H, respectively. *A* will then be as far above the horizontal plane at A_H as is required by the angle of dip at **A** along **A***O*, and likewise *B* will be as far above the horizontal plane at B_H as is required by the angle of dip at **B** along **B***O*.

Imagine now a vertical plane passed through AA_H and BB_H.

[2] One should observe that parallel lines are useless because no point of intersection can be located. Therefore it is well in the field to avoid directions nearly parallel, leading to an unstable solution by whatever method used, and to choose those directions, if possible, near to 90°, which angle gives the greatest accuracy of solution. Solutions from directions differing by less than 30° are untrustworthy.

It will cut the stratigraphic plane in the line AB and the horizontal plane in the line A_HB_H. Then imagine this last plane folded on the line A_HB_H as a hinge, down away from O, into the horizontal plane. The points A and B will rotate to the positions A' and B' respectively. The lines AA_H and BB_H remain perpendicular to the line A_HB_H during the rotation, with the result that AA' and BB' are at right angles to A_HB_H.

Turning now from the space diagram to its top view, or orthographic projection, we have the relations shown in Fig. 5 for Figs.

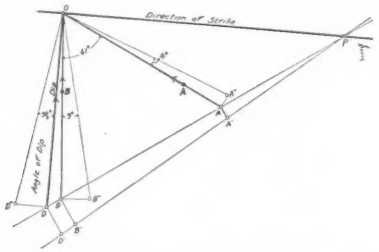


FIG. 5. Top view, orthographic projection, of the space diagram of Fig. 3.

1 and 3.[3] There is now no need for the points **A**, $\mathbf{A}_H$, A_H, **B**, $\mathbf{B}_H$, and B_H; so they are dropped. The line $A'B'$ will in general meet the line AB in some point, P, which point will necessarily be in the line of intersection of the stratigraphic plane and the horizontal plane because P lies in both planes. The point O is also on this line of intersection. Therefore this line of intersection is determined by P and O. This line, OP, of intersection of the stratigraphic plane with the horizontal plane is a horizontal line in the stratigraphic plane; and it therefore gives *the direction of strike*. A line at right angles to OP is in the direction of dip, looking at the line OP from the A and B side.

In particular, let us consider the true dip line through O, at right angles to OP, cutting the line AB in D. Let us pass a vertical plane through OD (see Figs. 3 and 4). Then OD is the

[3] It will be a useful exercise for the reader to construct a figure similar to Fig. 5 from the data of Figs. 2 and 4.

intersection of this plane with the stratigraphic plane, and OD_H is its intersection with the horizontal plane. The position of D' in the rotated plane PBB' is found by drawing a line from D, Fig. 5 (or D_H, Fig. 3), to $B'P$ at right angles to AB, meeting $B'P$ in the point D'. The line DD' then corresponds to AA' and BB'; *i.e.*, the length of DD' gives the height of D above the horizontal plane. Knowing now the height of D above the horizontal plane, let us rotate the vertical plane through OD about the line OD_H (directly below OD, see Fig. 3) as a hinge, into the horizontal plane. D will be rotated to the position D'', $\overline{DD''}$ being identically equal to $\overline{DD'}$ and at right angles to OD. The angle DOD'' will therefore be *the angle of dip* required.

To determine the lengths of AA' and BB' in the orthographic projection, one may rotate vertical planes through OA and OB down into the horizontal plane as shown in Fig. 5. This means that in practice one may draw the triangle AOB, $OA = OB$; then one may draw lines from O making angles with OA and OB equal to the respective observed components of dip along AO and BO. Perpendiculars to OA and OB at A and B drawn to these lines give the distances of A and B above the horizontal

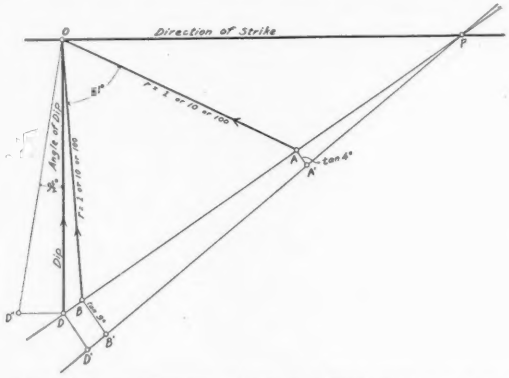


FIG. 6. Simplified arrangement of Fig. 5, plotted with a unit radius of 1, 10, or 100, so that the natural tangents of the angular dip components (α and β) can be plotted directly, and the tangent of the true dip (δ) can be measured at once as the length of the line $\overline{DD'}$ to the same scale.

plane. These distances are to be then transferred to AA' and BB'.

A more speedy and accurate way to determine the lengths of AA' and BB' is to choose the equal lengths OA and OB as some convenient unit, say one decimeter, and to lay off AA' and BB' *to the same scale* at once as the natural tangents of the observed components of dip along the lines OA and OB respectively. Fig. 6 shows this elementary solution complete with the fewest possible lines.

A consideration of two limiting cases of the above solution leads to a very much more accurate solution. Two of these arise in which the solution as outlined above is difficult or impossible.[4] The first of these limiting cases occurs when the two components of the dip are so nearly equal that the point P lies outside of the drawing.[5] The second occurs when the components of the dip are so small that the angle BPB' is very "thin," thus giving an unsatisfactory location of P.

There are two ways of overcoming the first difficulty, one of which is given here; the other is more complicated and less reliable than this. The method of overcoming the second difficulty is incorporated in the following discussion of the first:

Imagine the line AO extended beyond O to a point $-A$, so that the line AO is equal to the line $\overline{O\text{–}A}$. Then the point $-A$ will be as far *below* the horizontal plane as the point A is *above* it. See Fig. 4, the lefthand side, and Fig. 7, which latter corresponds to Fig. 3. Pass a vertical plane through B and $-A$, and rotate this plane into the horizontal plane on the line $\overline{B\text{–}A}$ as a hinge. B_1 will then lie on one side of the line B–A and $-A_1$ on the other. As in the construction explained above the intersection of the lines $\overline{B\text{–}A}$ and $\overline{B_1\text{–}A_1}$ will determine a point, $-P$, on the strike line through O. The line $\overline{O\text{–}P}$ is therefore a line

[4] The third limiting case, mentioned above, when the directions of the dip components approach parallelism is not considered because the solution then becomes unstable or indeterminate by *any* method.

[5] If the two dip components *are* equal, obviously the strike line is at right angles to the bisector of the angle AOB, and the line of dip *is* that bisector. The angle of dip may then be readily determined as above or as below.

of strike, and its direction may be measured. In this construction the point $-P$ always lies between the points B and $-A$.

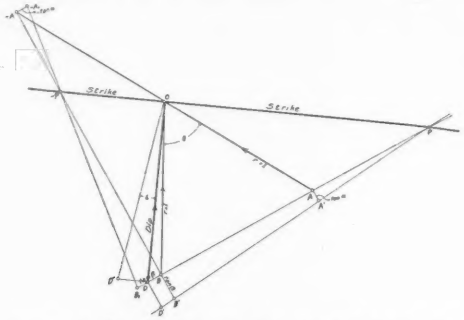


FIG. 7. The same as Fig. 6, but showing in addition the method of locating the point $-P$ to check the direction of strike.

Note that the location of $-P$ is more accurate than that of P, because the angle determining $-P$ is a function of the *sum* of the observed dip components while the angle determining P is a function of their *difference*. A full discussion of the relative merits of these two determinations of the line of strike would be beyond the purpose and scope of this paper. In any case where it is possible, however, the strike line should be determined by *both* P and $-P$, *i.e.*, P, O, and $-P$ should be in the same straight line.

To get rid of the "thin" intersections at P and/or $-P$ when the observed dip components are very small, one may multiply the natural tangents of these dip components by any number that will give satisfactory (30° or more) angles at P and/or $-P$. The natural tangents may be obtained graphically, as in Fig. 5 or from a table. A consideration of the pairs of similar triangles PAA' and PBB', and $-PBB_1$ and $-P$–A–A_1 (Figs. 7 and 8) will show that *proportional* variation of the pairs of lines AA' and BB', and BB_1 and $-A$–A_1 does not vary the positions of the points P and $-P$; and that it therefore does not affect the direction of the line of strike. The tangent of the angle of dip

as determined by this device will be as many times the tangent of the true angle of dip as the factor used in increasing the tangents of the dip components. Compare Fig. 8 with Fig. 7 to see the

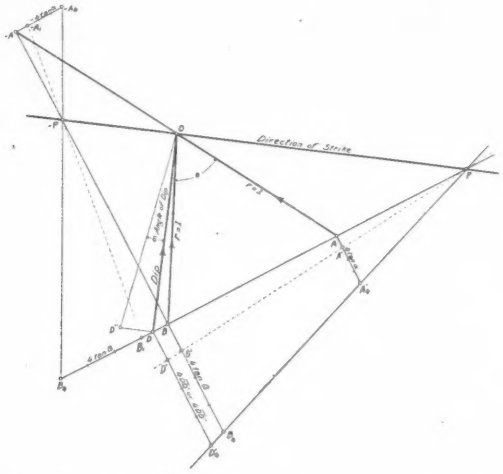


FIG. 8. The extension of the construction shown in Fig. 7 by multiplying the natural tangents of the dip angles by some convenient (integral) factor to secure a better location of the points P and $-P$, and thus a more accurate determination of the direction of strike in the line $\overline{-PP}$.

great increase in precision by this device. The accuracy of Fig. 8 is well within that of ordinary field observations.

The fact that the values of small (say, for our purposes, less than 10°) angles are nearly proportional to their natural tangents makes it possible for us to introduce another simplification of the solution when the angles are small, and to do away with the trigonometric function altogether. We may use *the dip angles themselves,* or any convenient multiple of them, in our construction. As a matter of fact, as we shall see in the formulas developed below, we are dealing with the *ratio* of the tangents of the two observed dip components; and hence the substitution of the angles themselves for their tangents introduces very little error over a considerable range of values (see Table I.).

We may now construct a figure as in Fig. 9, using only triangles, pencil, scale, and compass, laying off on our rotated perpendiculars *to any scale* the *angles* of the observed dip components *as linear units*. When the unit radius length of OA and OB is taken as one decimeter, a scale of one centimeter to

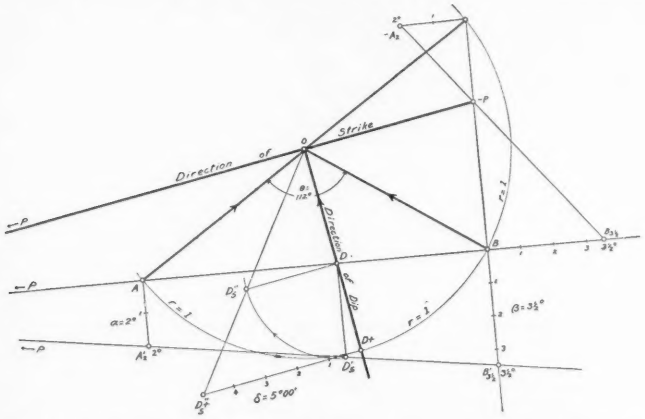


FIG. 9. Application of principles in Fig. 8 when point P lies outside the drawing. The figure also shows the angles themselves, in degrees, used in place of their natural tangents. See text for the limitations of this substitution. Note especially the construction by which the angle DOD_5'' may be read to the same scale as are α and β.

one degree is in many cases a convenient linear angle scale on the rotated perpendiculars. Note particularly, however, that the triangle ODD_5'' which determines the angle of dip *must* be changed to the similar triangle $OD+D_5+''$ with the unit side $\overline{OD+}$ equal to $\overline{OA}$ and $\overline{OB}$ in order that the angle of dip may be read on the line $\overline{D+D_5+''}$ to the same scale as the observed dip components were laid off on their rotated perpendiculars.

This method can be applied quickly to practically any case, and it will give results entirely consistent in accuracy with ordinary field observations. By using care and a properly sharpened wedge-pointed drawing pencil results may be obtained for small angles far within the limits of accuracy of any but the most re-

fined field observations, and this with but a five-centimeter radius circle on a sheet of 8 by 11 typewriter paper. Fig. 10 shows such

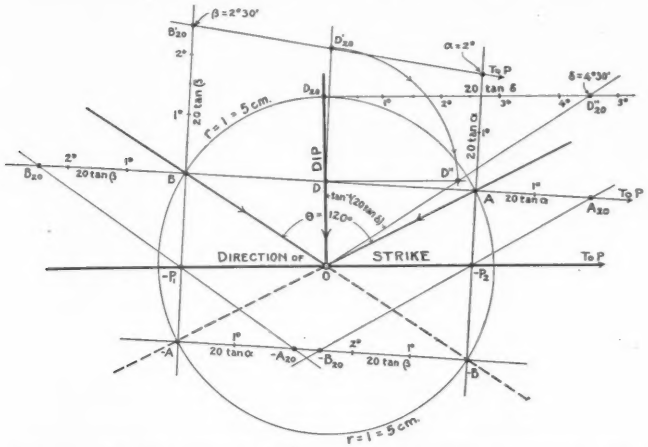


FIG. 10. The full solution of a problem, with checks on opposite sides of the unit circle, by the principles illustrated in Figs. 8 and 9. This solution is for small angles in the ratio of 2 to 2½, or for angles with their natural tangents in the ratio of 2 to 2½, or for gradients in the ratio of 2 to 2½. The original drawing, carefully constructed, using angles in place of their tangents, gave the value of the true dip to but one minute of arc different from the computed value.

a drawing with all checks which gives the direction of strike correct to ten minutes and the angle of dip correct to within two minutes.

If our field data happen to be in the form of gradients, *e.g.*, feet to the mile, meters to the kilometer, etc., precisely the same construction holds as for the natural tangents; for the gradients are strictly proportional to the natural tangents of the angular values of the dip components. No error whatsoever enters the construction in plotting the gradients to any scale on the rotated perpendiculars. As, after all (see formula below), we are concerned *only with their ratio,* the units in which the vertical and the horizontal measurements may have been made make no dif-

ference to the construction, other than that, of course, the components of the same problem must be in the same units. Thus, whether it be inches to the rod, thousandths of a foot to the mile, feet to the mile, tens of thousands of feet to the mile, millimeters to the kilometer, meters to the kilometer, kilometers to the kilometer, or etc., etc., the construction is identically the same. We may therefore take Fig. 9 as being for feet to the mile or tens of meters to the kilometer; and we may take Fig. 10 as being for meters to the kilometer or hundreds of feet to the mile. This construction is therefore rapidly and conveniently applicable to all classes of gradient problems.

The dip or gradient in any direction may be obtained by rotating into the horizontal plane the vertical plane of the given direction through O. Fig. 11 shows the construction when the point

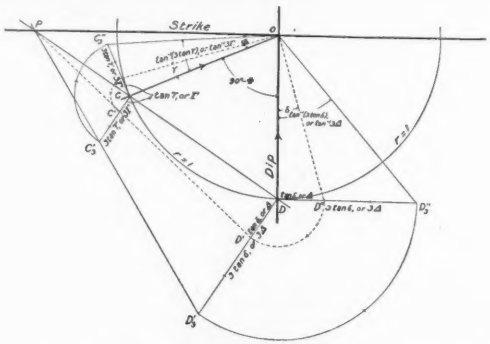


FIG. 11. The complete construction to illustrate the determination of a dip or gradient in a given direction (that of the line CO) when the dip and strike are given, the point P falling within the limits of the drawing. The gist of the constructon is in determining the length of the line $\overline{C_3'C}$. The dotted lines indicate the solution without increasing the tangents or gradients by a constant multiplier. Note the increase in accuracy by so doing.

P lies within the limits of the drawing. The direction of CO being given, the height of C, on the unit circle, above the horizontal plane may be determined by drawing the line DC cutting the given strike line in the point P, and then rotating the vertical

plane through DC down into the horizontal plane. D rotates to D', C to C'. The length of the line CC' gives tan γ, the tangent of the required angular dip, or Γ the required gradient dip. The angle γ may now be determined in the rotated vertical plane through CO by laying off the length of CC' at right angles to CO and joining the extremity of that line with O. Great increase in accuracy may be obtained by multiplying tan δ or Γ by a convenient factor (3 in the case of Fig. 11).

If, however, the point P falls outside the limits of the drawing, the construction to be used is shown in Fig. 12. It will be noticed

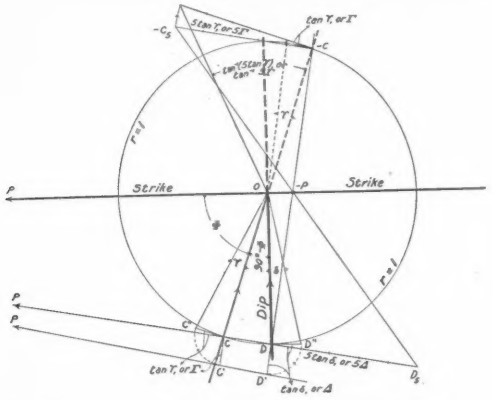


FIG. 12. As Fig. 11, the determination of a dip or gradient in a given direction (that of CO), but when the point P lies outside the drawing. The gist of the construction lies in the location of the point $-P$ by the line $\overline{CC'}$ so that the line $\overline{D_5-P}$ may be drawn to locate the point $-C_5$ and thus determine the length of the line $-C-C_5$ which is proportional (according to the factor used in plotting D_5, 5 in this drawing) to the tangent of γ or to the gradient Γ, the angular dip or gradient sought.

that this construction is necessary when C is near to D, *i.e.*, when the given Φ is near 90°. Use is here made of the parts of the dip lines below the horizontal plane. The point $-P$ is located on the strike line by its intersection with the line joining D and $-C$ (on the unit circle). On rotating the vertical plane through D and $-C$ into the horizontal plane, D falls at D_5, say, using a

convenient factor, as five in Fig. 12. The line $\overline{D_5\text{–}P}$ will cut the perpendicular to the line $\overline{D\text{–}C}$ from $-C$ at the point $-C_5$, which is the rotated position of $-C$, corresponding in its relation to $-C$ to that of D_5 with reference to D. The length of the line $\overline{-C\text{–}C_5}$ is therefore the proportional tan γ or Γ required,—in the case of Fig. 12, 5 tan γ, or 5 Γ.

If the angles themselves are substituted for their tangents, the lines $\overline{CC_3'}$ in Fig. 11, and $\overline{-C\text{–}C_5}$ of Fig. 12, may be read in angles directly, according to the scale used in plotting $\overline{DD_3'}$ and $\overline{DD_5}$, respectively.

The direction of a given dip or gradient may be found as follows: First, one should see that the given component dip is *less*

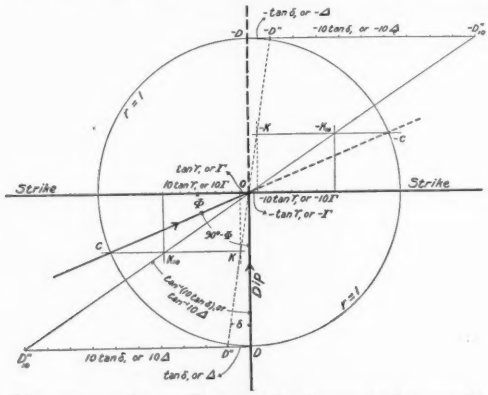


FIG. 13. The construction to illustrate the determination graphically of the direction of a given angular dip or gradient, γ or Γ, respectively. The gist of the construction lies in the location of the point K_{10} a point on the line $\overline{D_{10}''\text{—}D_{10}''}$ distant 10 tan γ or 10Γ from the dip line $\overline{D\text{—}D}$, through which a line $K_{10}C$ cuts the unit circle in a point C which determines the required direction CO. Any other convenient factor than 10 might be used. Small angles may be used in place of their tangents. The check construction in the opposite quadrant of the unit circle is given. The construction without the use of a factor is shown in dotted lines; but note the great increase in accuracy by the use of the factors.

than the given true dip. Then (see Fig. 13) the vertical plane through the true dip line should be rotated into the horizontal

plane, thus bringing the line DO to the position $D''O$. It is now required to find a point, K, on $D''O$, which was distant tan γ or Γ above the horizontal plane on DO. This point K is located at the intersection of the line $D''O$ with a line parallel to DO and distant tan γ or Γ from DO. A line through K parallel to the strike line gives the corresponding point, C, on the unit circle. CO is the required line of the given component dip, γ or Γ, and its direction, Φ, may be measured. Multiplying tan γ or Γ by a suitable factor greatly increases the accuracy of the solution; and the location of the corresponding negative K in the diagonally opposite quadrant furnishes a check on the line CO, for the line $\overline{CO-C}$ should be a straight line. These phases of the solution are all shown in detail in Fig. 13. Small angles may be substituted for their tangents without appreciable error.

MATHEMATICAL DEVELOPMENT.

For the development of the mathematical formulas, let us consider Fig. 14, adapted from and constructed as Figs. 5 and 6.

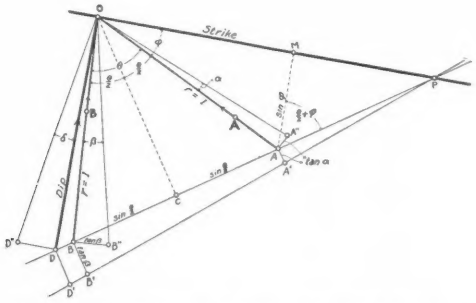


FIG. 14. The figure for reference in the mathematical discussion in the text, is adapted like Fig. 6 from the field conditions shown in Fig. 1.

To recapitulate the meanings of the symbols used: α = the lesser observed angular dip component; β = the greater observed angular dip component; γ = any third required angular dip component except the true or maximum; δ = the maximum or true angular

dip; A = the lesser observed gradient dip component; B = the greater observed gradient dip component; Γ = any third required gradient dip component except the true or maximum dip; Δ = the true or maximum gradient dip; θ = the angle between the observed directions of the dip components; ϕ = the angle between the direction of strike and the observed direction of the lesser (α or A) dip component; Φ = the angle between the direction of strike and any third direction of dip component.

In Fig. 14 the line OC is the bisector of the angle θ; and it is therefore perpendicular to BA at its midpoint. AM is the perpendicular from the point A onto the line OP. We have OB equal to OA, and both, for simplicity, equal to unity.[6] Using this fact and the symbols defined in the preceding paragraph, we have the following identities for the numerical lengths of the lines to the chosen scale:

$$\overline{AA'} \equiv \tan\alpha, \qquad \overline{BB'} \equiv \tan\beta, \qquad \overline{BA} \equiv 2\sin\frac{\theta}{2},$$

$$\overline{AM} \equiv \sin\varphi, \qquad \angle\, MAP \equiv \frac{\theta}{2} + \varphi, \qquad \frac{\overline{DD'}}{\overline{OD}} \equiv \tan\delta.$$

It is required to find $\tan\phi$ and $\tan\delta$; θ, α, and β being given. In the triangle AMP,

$$\sin\varphi = \overline{AP}\cdot\cos\left(\frac{\theta}{2} + \varphi\right)$$
$$= \overline{AP}\left(\cos\frac{\theta}{2}\cdot\cos\varphi - \sin\frac{\theta}{2}\cdot\sin\varphi\right).$$

Dividing by $\cos\phi$,

$$\tan\varphi = \overline{AP}\left(\cos\frac{\theta}{2} - \sin\frac{\theta}{2}\cdot\tan\varphi\right),$$

or,

$$\tan\varphi = \frac{\overline{AP}\cdot\cos\frac{\theta}{2}}{1 + \overline{AP}\cdot\sin\frac{\theta}{2}}. \qquad (1)$$

[6] Any convenient length may be arbitrarily chosen as this unit.

From the similar triangles, $PB'B$ and $PA'A$,

$$\frac{\overline{AP}}{\overline{AA'}} = \frac{\overline{AP} + \overline{BA}}{\overline{BB'}}, \qquad \text{or,} \qquad \frac{\overline{AP}}{\tan\alpha} = \frac{\overline{AP} + 2\sin\frac{\theta}{2}}{\tan\beta};$$

whence,

$$\overline{AP} = \frac{2\sin\frac{\theta}{2}}{\frac{\tan\beta}{\tan\alpha} - 1}. \tag{2}$$

Substituting (2) in (1), we have for the numerator of (1),

$$\overline{AP}\cdot\cos\frac{\theta}{2} = \frac{2\sin\frac{\theta}{2}\cdot\cos\frac{\theta}{2}}{\frac{\tan\beta}{\tan\alpha} - 1} = \frac{\sin\theta}{\frac{\tan\beta}{\tan\alpha} - 1};$$

and for the denominator of (L),

$$1 + \overline{AP}\cdot\sin\frac{\theta}{2} = 1 + \frac{2\sin\frac{\theta}{2}}{\frac{\tan\beta}{\tan\alpha} - 1}\cdot\sin\frac{\theta}{2},$$

$$= \frac{\frac{\tan\beta}{\tan\alpha} - \left(1 - 2\sin^2\frac{\theta}{2}\right)}{\frac{\tan\beta}{\tan\alpha} - 1},$$

$$= \frac{\frac{\tan\beta}{\tan\alpha} - \cos\theta}{\frac{\tan\beta}{\tan\alpha} - 1}.$$

(1) therefore becomes:

$$\tan\varphi = \frac{\overline{AP}\cdot\cos\frac{\theta}{2}}{1 + \overline{AP}\cdot\sin\frac{\theta}{2}} = \frac{\sin\theta}{\frac{\tan\beta}{\tan\beta} - 1}\cdot\frac{\frac{\tan\beta}{\tan\alpha} - 1}{\frac{\tan\beta}{\tan\alpha} - \cos\theta},$$

$$= \frac{\sin\theta}{\frac{\tan\beta}{\tan\alpha} - \cos\theta}; \tag{3}$$

which, being interpreted, means that the tangent of the angle between the direction of strike and either observed direction of dip component is equal to the sine of the angle between the two directions of dip components, divided by the ratio of the tangent of the observed dip component, whose direction *is not* required, to the tangent of the observed dip component with whose direction the strike direction *is* required, less the cosine of the angle between the observed directions of the dip components.

For it may be shown in a way similar to the above proof that, if ϕ_B is the angle between the observed dip direction along BO and the direction of strike, then,

$$\tan \varphi_B = \tan (\theta + \varphi) = \frac{\sin \theta}{\frac{\tan \alpha}{\tan \beta} - \cos \theta}. \qquad (3a)$$

The cotangents may be substituted for the tangents in (3) and (3*a*), but there is no advantage in this change.

To determine the angle of dip, we observe in Fig. 14 that the lines AM and AA' are parallel respectively to the lines DO and DD'. We have therefore from the pencil P–$D'DO$ the relation:

$$\frac{\overline{DD'}}{\overline{DO}} = \frac{\overline{AA'}}{\overline{AM}} = \frac{\overline{BB'}}{\overline{BN}};$$

or,

$$\tan \delta = \frac{\tan \alpha}{\sin \varphi} = \frac{\tan \beta}{\sin \varphi_B}, \qquad (4)$$

which means that the tangent of the angle of dip is equal to the ratio of the tangent of either observed angular dip component to the sine of the angle between the direction of that dip component and the direction of strike.

If the dips have been observed in the form of gradients, *e.g.*, feet to the mile or meters to the kilometer, the gradient number will be the ratio of the vertical leg of a right triangle to the horizontal one (*e.g.*, so many feet to 5,280 feet or so many meters to 1,000 meters); and it will therefore be *proportional* to the

tangent of the angle of the dip component. That is, the gradients will differ from the tangents of the angular dips by a constant multiplier dependent in value upon the particular units used for the gradients (5,280 in the first case above, 1,000 in the second). Let us call this constant k. Then,

$$\tan \alpha = k\mathrm{A},\ \tan \beta = k\mathrm{B},\ \tan\ \delta = k\Delta,$$

and likewise for any other dip component, as, $\tan \gamma = k\ \Gamma$. Therefore

$$\frac{\tan \alpha}{\tan \beta} = \frac{k\mathrm{A}}{k\mathrm{B}} = \frac{\mathrm{A}}{\mathrm{B}},\quad \frac{\tan \beta}{\tan \alpha} = \frac{k\mathrm{B}}{k\mathrm{A}} = \frac{\mathrm{B}}{\mathrm{A}},\quad \frac{\tan \delta}{\tan \alpha} = \frac{k\Delta}{k\mathrm{A}} = \frac{\Delta}{\mathrm{A}},\quad \text{etc.}$$

Hence, for gradient measurement, in whatever units the vertical and horizontal portions may be taken, formulas (3) and (4) become:

$$\tan \varphi = \frac{\sin \theta}{\frac{\mathrm{B}}{\mathrm{A}} - \cos \theta}, \tag{5}$$

$$\tan \varphi_B = \tan (\theta + \varphi) = \frac{\sin \theta}{\frac{\mathrm{A}}{\mathrm{B}} - \cos \theta}, \tag{5a}$$

$$\Delta = \frac{\mathrm{A}}{\sin \varphi} = \frac{\mathrm{B}}{\sin \varphi_B}. \tag{6}$$

A consideration of formulas (4) and (6) will give us the dip in any given direction or the direction of any given dip, when the true, or maximum, dip or gradient and the direction of strike are known. Let γ and Γ be any dip or gradient respectively, and Φ the angle between their direction and the direction of strike. Then, by analogy with (4)[7],

$$\tan \delta = \frac{\tan \gamma}{\sin \Phi};$$

and by analogy with (6),

$$\Delta = \frac{\Gamma}{\sin \Phi}.$$

[7] In (4) α and β are *any* dip components, so the formula holds equally well for γ.

We have, therefore,

$$\tan \gamma = \tan \delta \cdot \sin \Phi; \tag{7}$$

$$\Gamma = \Delta \cdot \sin \Phi; \tag{8}$$

$$\sin \Phi = \frac{\tan \gamma}{\tan \delta}; \tag{9}$$

$$\sin \Phi = \frac{\Gamma}{\Delta}. \tag{10}$$

The geometrical constructions for the solution of these inverse problems will be found in Figs. 11, 12, and 13. The angle Φ always lies on the side of the strike line on which the stratigraphic plane is *above* the horizontal plane; but to determine whether it is in the quadrant to the right or to the left of the true dip line, looking down the stratigraphic plane, when it is to be evaluated from a given γ or Γ requires *a priori* knowledge, from the field conditions or from the office requirements, of the quadrant in which the given γ or Γ is to be taken. Φ lies in the same quadrant as γ or Γ.

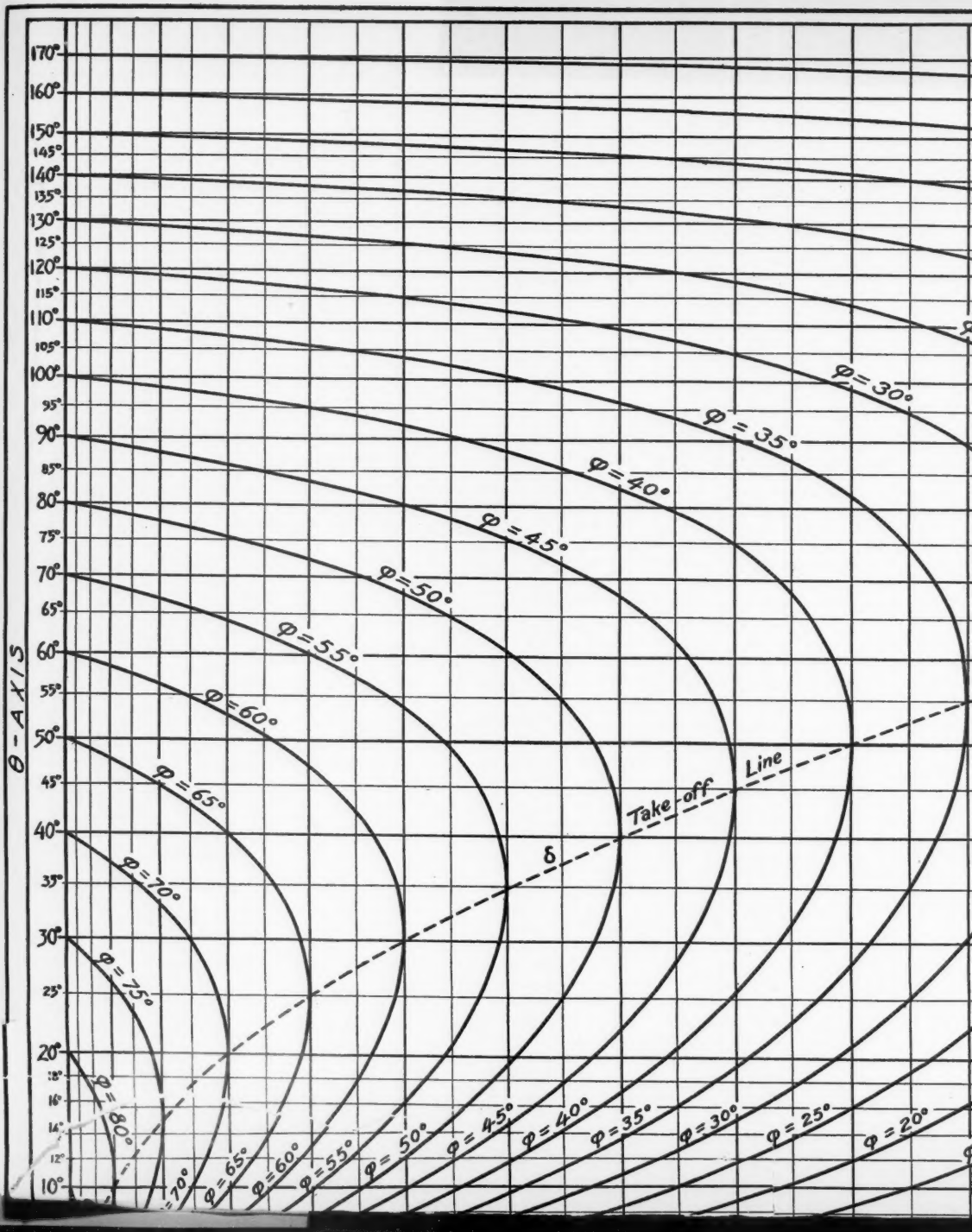
Although the formulas of this mathematical development give correct results, caution must be exercised at times in using and in interpreting the algebraic signs.

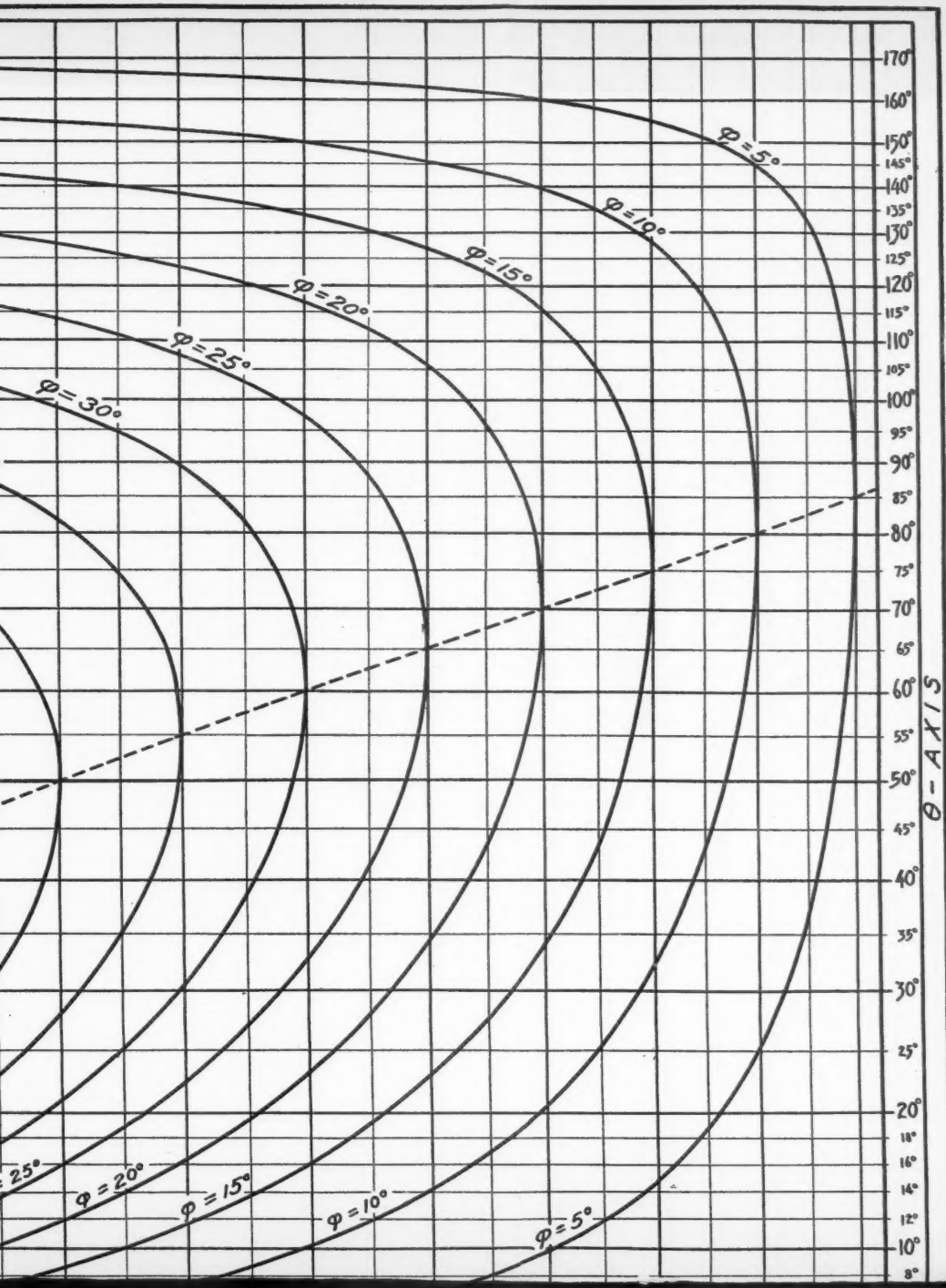
USE OF THE DIAGRAMS.

Families of curves may be constructed from the formulas above in such a way that, interpolating when necessary, any problem, direct or inverse, of the nature treated in this paper may be solved within the degree of precision justified by any but the most refined (and unusual) field work, excepting in the neighborhood of certain limiting cases, which problems never arise in practice. Four ways of doing this are shown in Plates I., II. and Figs. 15, 16. The first two deal with the dips as angles, the second two consider them as gradients. There is a considerable range of values, however, over which the gradient diagrams may be employed, using the degrees of the angular dips as gradients, not angles, in a way similar to that explained in the method by descriptive geometry above.[8]

[8] The discussion of the limits of allowable error in this substitution would take us too far afield in abstract mathematics for the scope of this paper.

PLATE I.


θ - AXIS
170°
160°
150°
145°
140°
135°
130°
125°
120°
115°
110°
105°
100°
95°
90°
85°
80°
75°
70°
65°
60°
55°
50°
45°
40°
35°
30°
25°
20°
18°
16°
14°
12°
10°
φ = 30°
φ = 35°
φ = 40°
φ = 45°
φ = 50°
φ = 55°
φ = 60°
φ = 65°
φ = 70°
φ = 75°
φ = 80°
Take-off Line
δ
φ = 70°
φ = 65°
φ = 60°
φ = 55°
φ = 50°
φ = 45°
φ = 40°
φ = 35°
φ = 30°
φ = 25°
φ = 20°


φ=5°
φ=10°
φ=15°
φ=20°
φ=25°
φ=30°
170°
160°
150°
145°
140°
135°
130°
125°
120°
115°
110°
105°
100°
95°
90°
85°
80°
75°
70°
65°
60°
55°
50°
45°
40°
35°
30°
25°
20°
18°
16°
14°
12°
10°
8°
θ-AXIS

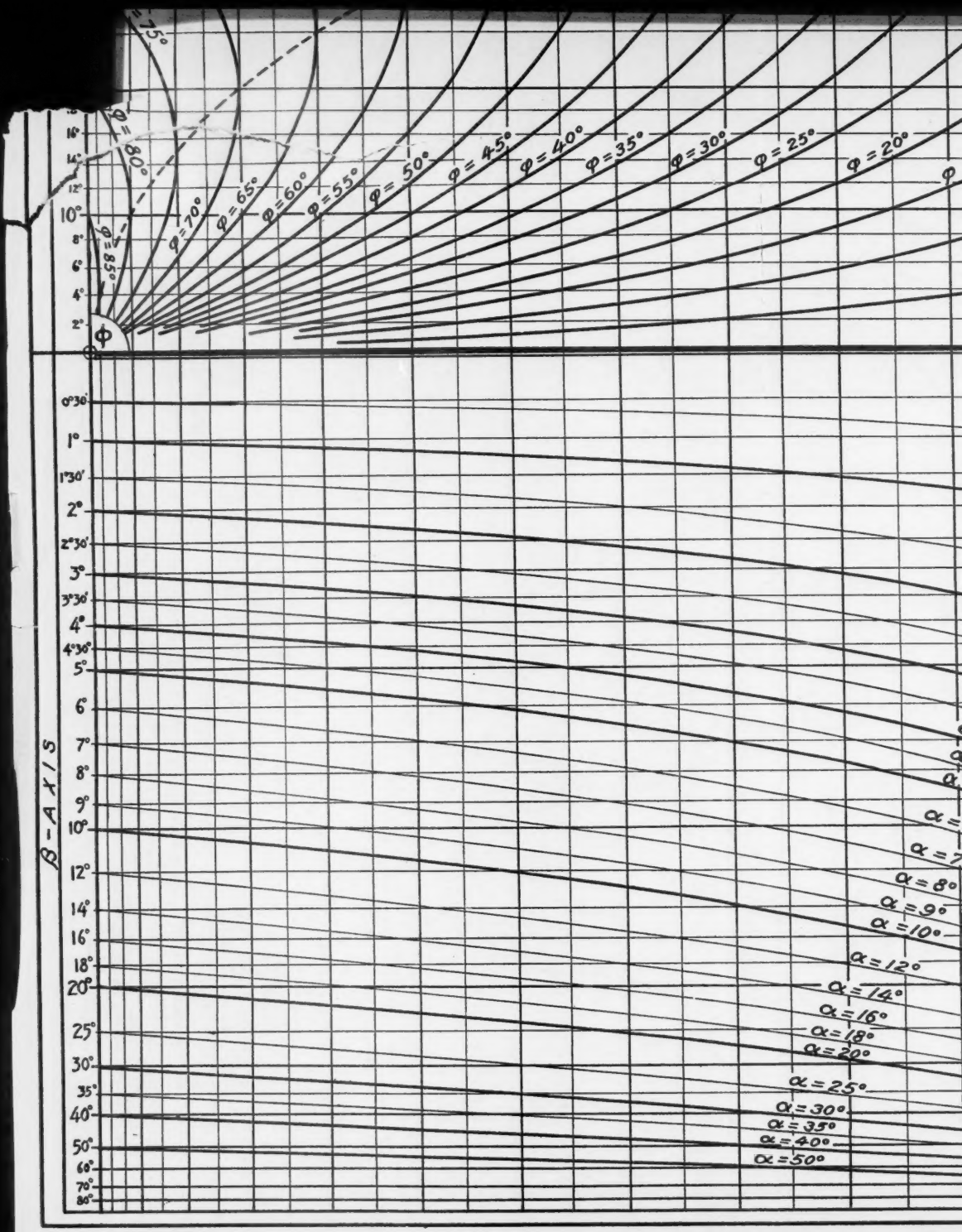
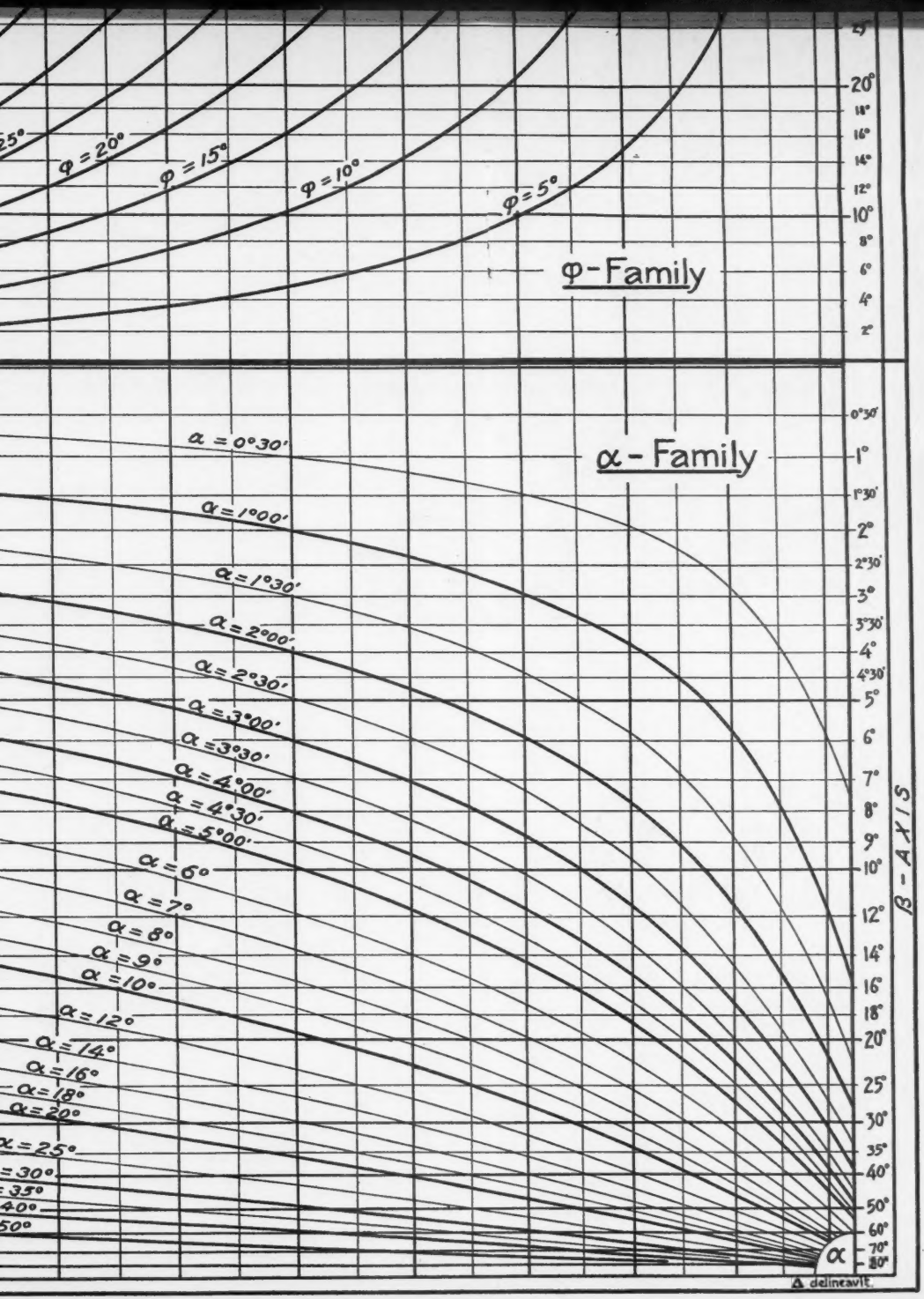


PLATE I. Diagram by which to determine strike and angular dip from any two observed components, and to determine t
angular dip and strike are given; a rectangular form. See the text for



ents, and to determine the angular dip in any given direction or the direction of any given angular dip when the true orm. See the text for the explanation of the use of the diagram.

Large portions of these diagrams would be beyond the limits of feasible drawings if they were plotted on ordinary rectangular coördinates; therefore, to bring in outlying portions of the curves for use and to make the absolute amount of error in the solutions

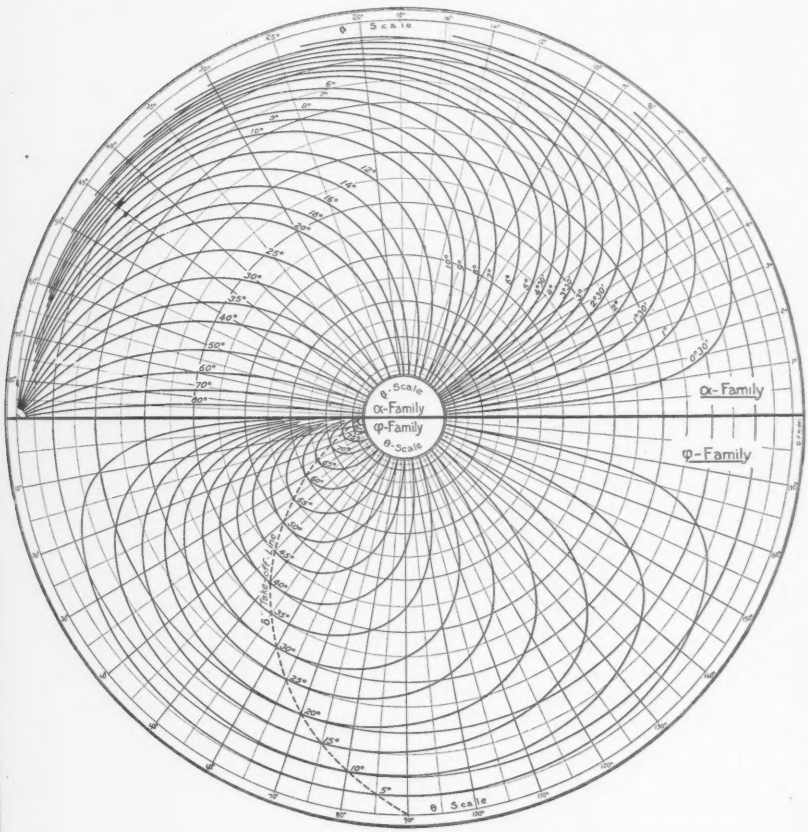


FIG. 15. Diagram by which to determine the strike and angular dip from any two observed components, and to determine the angular dip in any given direction or the direction of any given angular dip when the true angular dip and the strike are given; a circular form. See the text for the explanation of the use of the diagram.

more nearly constant over a larger domain than is possible with rectangular coördinates, suitable hyperbolic transformations have been made before plotting the curves.[9] Two diagrams have been prepared in a rectangular form (Plates I. and II.), and two have been plotted in a circular form (Figs. 15 and 16). Other arrangements are possible. Each of these diagrams will furnish the solution of a double infinity of problems of either the direct or of the inverse type.

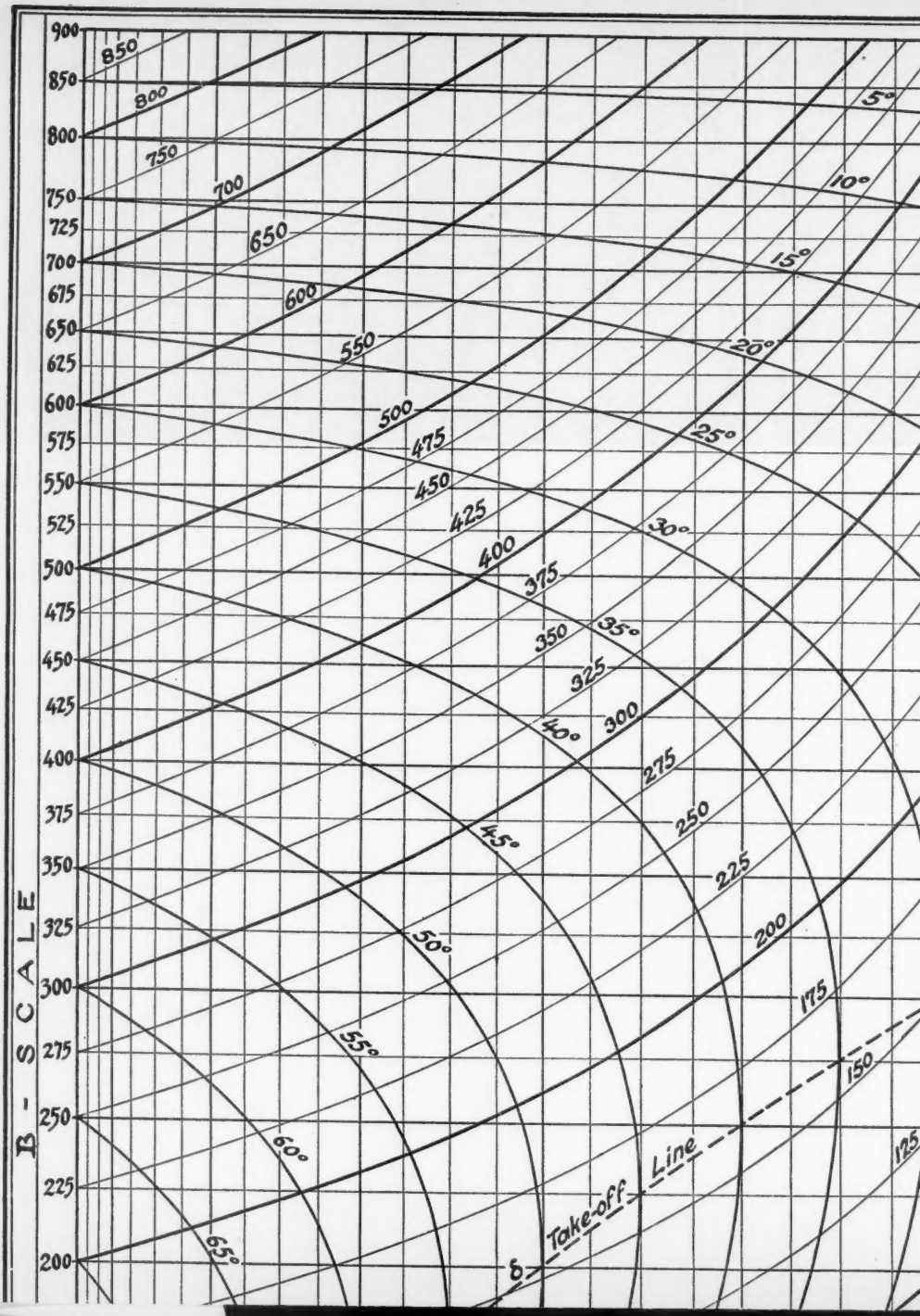
The principle of the use of the diagrams is the same for all of them. One takes the larger observed dip component (β or B), follows it into the diagram (always on a straight line) till it cuts the member of the "α-family" of curves (those *not* coming from the origin) corresponding in value to the lesser dip component (α or A), interpolating, of course, if necessary. From that point one follows the vertical lines in Plates I. and II. or the circular lines in Figs. 15 or 16 till he reaches the transverse line (always a straight line) corresponding in value to the angle θ, as read on the θ-scale, between the two observed directions of the dip components. In Plate II. and Fig. 16, these are on the same set of lines as the straight dip lines, in Plate I. and Fig. 15, they are on different sets of lines. In all the diagrams these lines are labeled as the β or B-scale for the dips and the θ-scale for the angles of intersection of the observed dip component directions.

The position to which one has now come, as determined by reading that position from the "ϕ-family" of curves (those which all begin from the origin), will give the angle (ϕ) between the direction of strike and the direction of the lesser dip component, measuring that angle on the side *away* from the other, greater, observed dip component.

Following now in the ϕ-family of curves till one reaches the "δ take-off line," one then leaves that family and follows the vertical (in Plates I. and II.) or circular (in Figs. 15 and 16) lines back to the "α-curve" from which he started. The reading then on the β-scale will be the true or maximum dip (δ) or

[9] One might say that infinity has been brought in for inspection, if desired. It is bottled up in the completed circle of the diagram of Fig. 16. It lies just outside of certain edges of the other diagrams.

PLATE II.


B - SCALE
900
850
800
750
725
700
675
650
625
600
575
550
525
500
475
450
425
400
375
350
325
300
275
250
225
200
850
800
750
700
650
600
550
500
475
450
425
400
375
350
325
300
275
250
225
200
175
150
125
5°
10°
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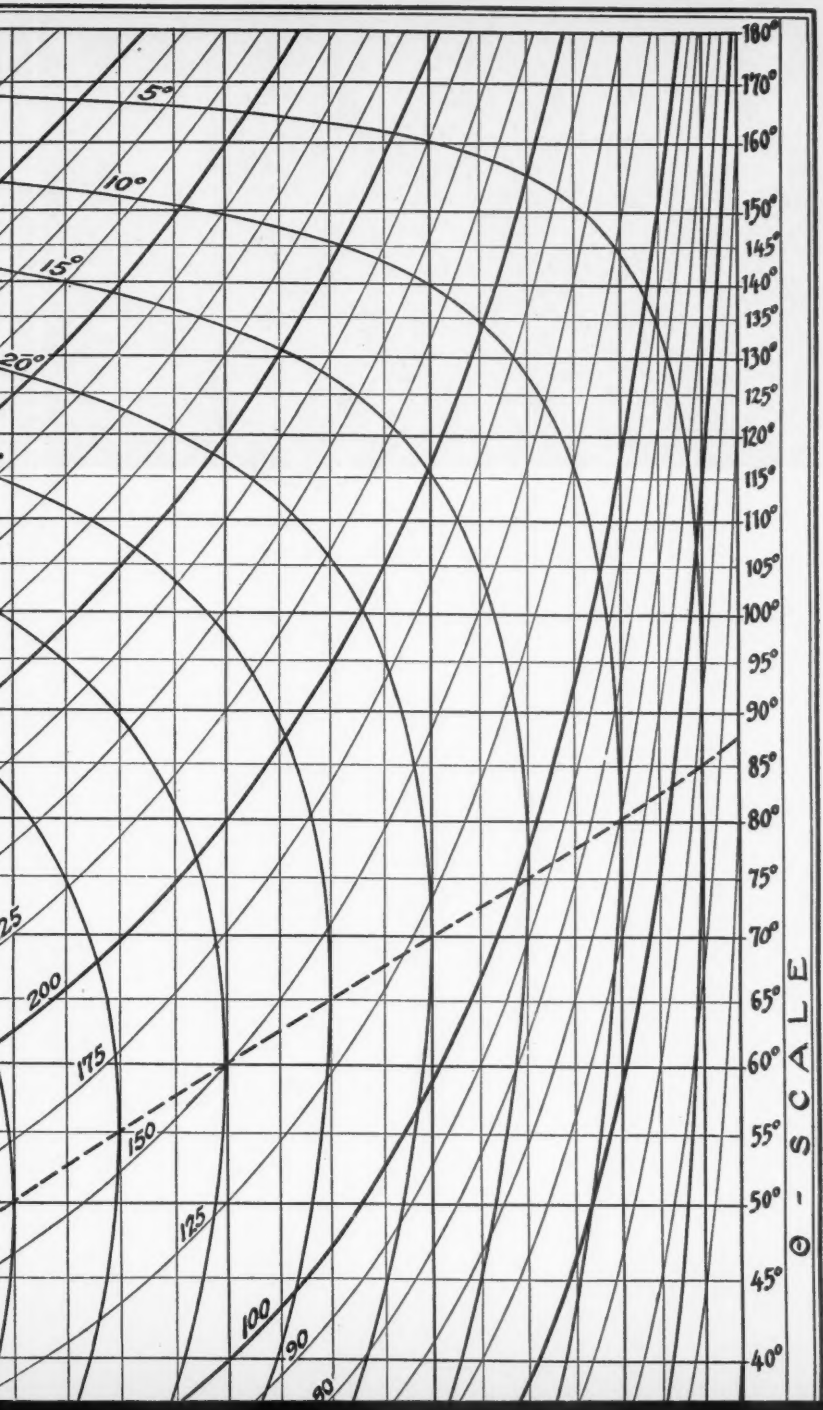
35°
40°
45°
50°
55°
60°
65°
δ
Take-off Line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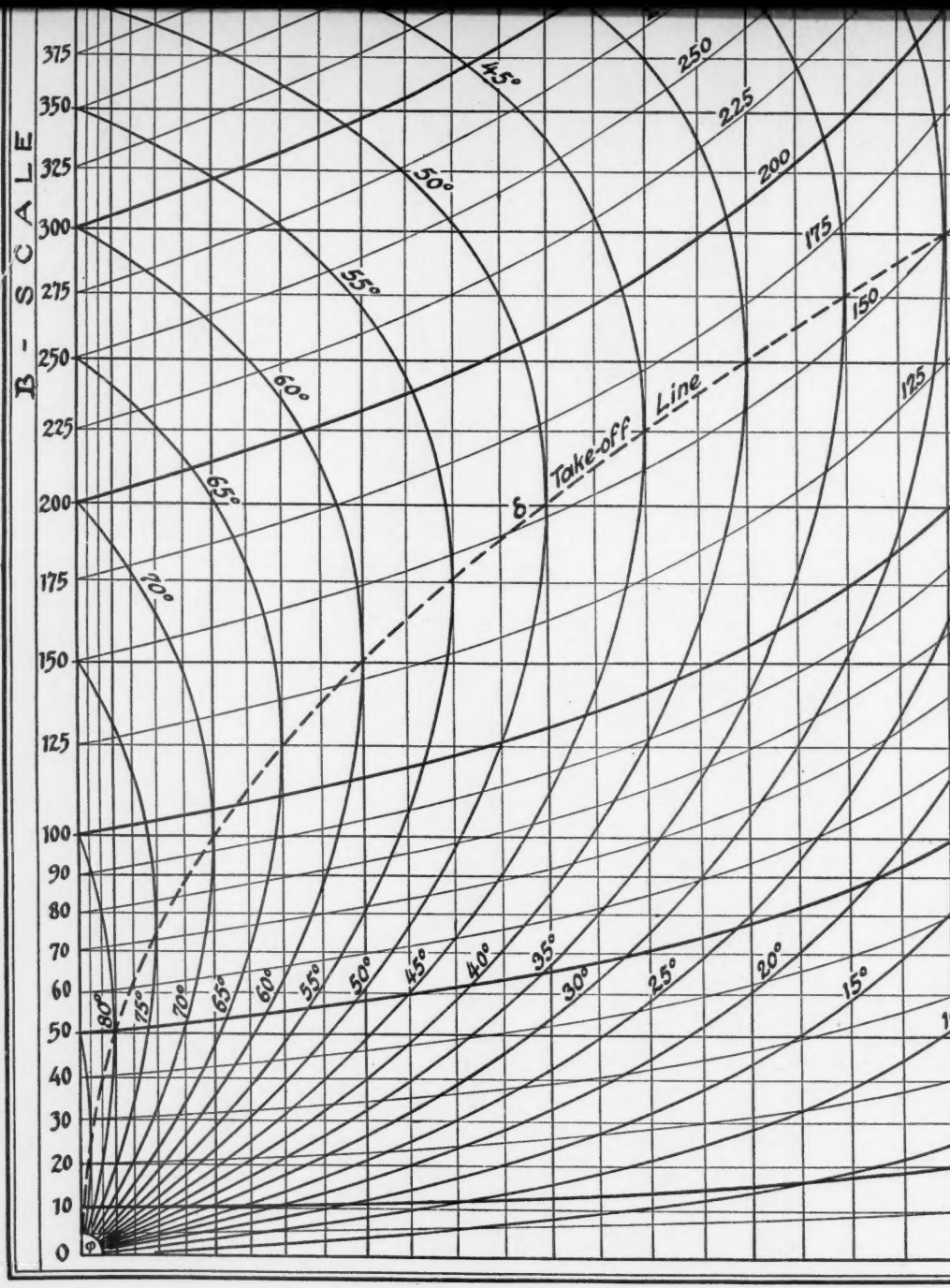
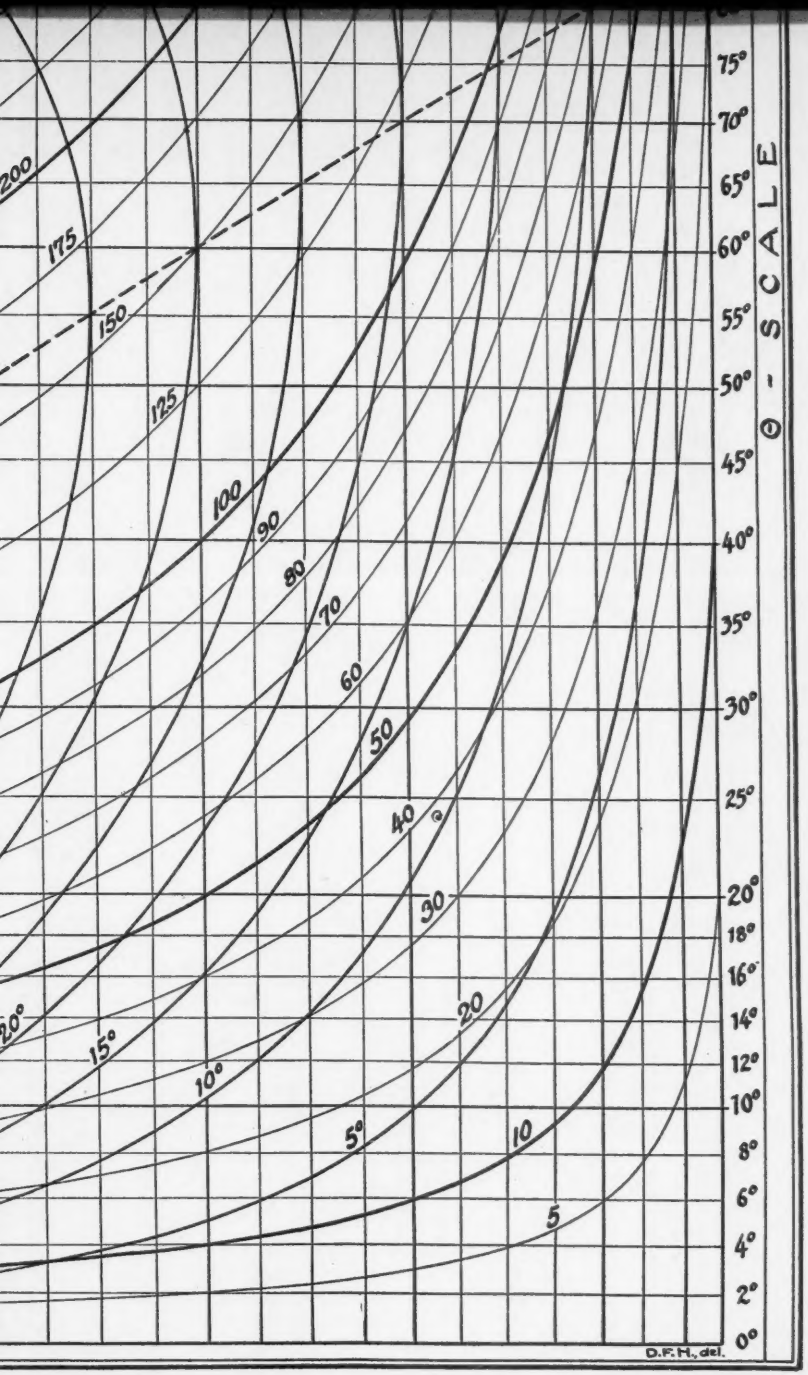


PLATE II. Diagram by which to determine strike and gradient dip from any two observed components, and of any given gradient dip when the true gradient dip and the strike are given; a rectangular form. See the text dips, or even small angles themselves in place of their tangents, may be used with this diagram.



served components, and to det ermine the gradient dip in any given direction or the direction
ar form. See the text for the explanation of the use of the diagram. Tangents of angular
gram.

gradient (Δ). Interpolation in the ϕ-family of curves is best made at right angles to the curves.

A definite example may be followed out in this way: Suppose that the gradient dip components are 90 and 175 vertical units to some horizontal unit, it makes no difference what, say feet to the mile, and that the angle between these components is 80°. Plate II. may be used. Following the line 175 to the right from the B-scale, and the curve 90 to the right and up from the B-scale, we readily determine their point of intersection. From this point we go up parallel, by eye estimation, to the vertical lines till we encounter the horizontal line of 80° leading from the θ-scale on the left. Interpolating our position now in the somewhat parabolic set of curves, the ϕ-family, roughly at right angles to the curves and not along the straight lines, we find that we are at about 29°. This angle is ϕ, the angle between the direction of the lesser, 90, dip component and the direction of strike. But this angle is always to be measured *away* from the direction of the larger, 175, dip component.

If we now keep our position between the curves $\phi = 30°$ and $\phi = 25°$ and travel following them till we meet the "δ take-off line," and from there follow the vertical lines, keeping carefully parallel to the verticals, we come to the 90-line again. Our position here, as read on the B-scale on the left, gives the true dip, about 186 feet to the mile.

To determine the direction of a given dip, one goes into the diagram with the true dip on the β or B-scale till he encounters the α-curve of the dip whose direction he wishes to determine, then one follows the vertical or circular lines to the "δ take-off line"; the reading at that point of the "δ take-off line" on the θ-scale is the required angle between the direction of the given true dip and the required direction of the given dip component. As this direction may lie on either side of the true dip direction, the appropriate one must be chosen according to the demands of the field or office.

In particular, suppose we wish the direction of a dip of 8° on a stratum whose true dip is 12°. Referring to Plate I., we

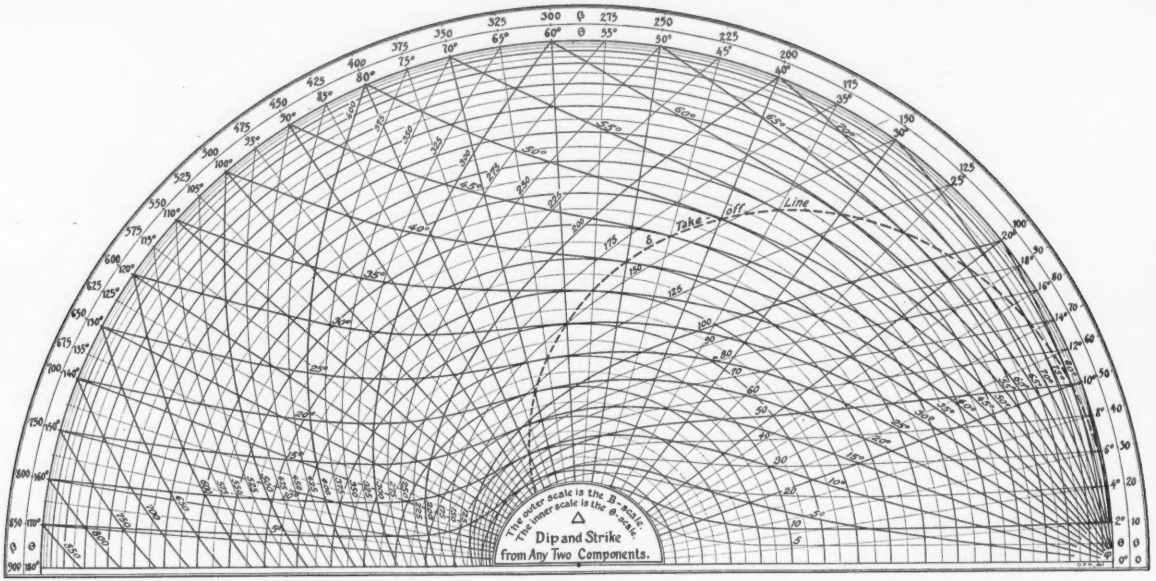


FIG. 16. Diagram by which to determine strike and gradient dip from any two observed components, and to determine the gradient dip in any given direction or the direction of any given gradient dip when the true gradient dip, and strike are given; a semi-circular form. See the text for the explanation of the use of the diagram. Tangents of angular dips, or even small angles themselves in place of their tangents, may be used with this diagram.

follow the 12°-line, horizontal in the lower part of the diagram, till we meet the 8°-curve in the same part of the diagram. Then we go up parallel to the verticals till we meet the "δ take-off line." The reading then on the θ-axis, to right or left, is the angle required, in this case about 48½°. This is the angle between the direction of true dip and the direction of a dip of 8°.

To determine the dip in a given direction, one goes into the diagrams on the θ-scale with the angle between the given directions of required dip and true dip, till one reaches the "δ take-off line." Thence one follows the vertical or circular lines to the line of the β or B-scale having the value of the given true dip. The reading of this point in the α-family of curves (those *not* beginning at the origin) will be the dip, γ or Γ, sought for.

A specific example may be worked as follows: Suppose we have given a true dip of 225 meters to the kilometer, and it is desired to know the dip in a direction 40° from the direction of true dip. Let us take Fig. 16 this time, and go into the diagram on the radius 40°. When we come to the "δ take-off line" we follow the circle to the left till we meet the radius 225 (on the outer scale). We now read by interpolation our position in the α-family of curves, those which have numbers not degrees. This reading, about 172, is the gradient, in meters to the kilometer, required.

Any of the four diagrams may be used for all of the three types of problems just given. These diagrams give results in general of sufficient precision for any but the most refined work. Diagrams could be made, however, large enough to give any degree of precision.

An interesting feature of the diagrams of Plate II. and Fig. 16 is that they can be used for any gradient units whatsoever, and with negligible error for small angles, say not over 10°.[10] For gradients the units may be inches to the rod, feet to the mile, tens of thousands of feet to the mile, thousandths of a foot to the mile, hundredths of a millimeter to the meter, millimeters to the kilometer, meters to the kilometer, kilometers to the kilometer,

[10] The amount of error for angles rapidly approaches zero as the angles become less than 10°.

semi-circular form. See the text for the ... themselves in place of their tangents, may be used with this diagram.

TABLE I.

SHOWING THE RELATIVE ACCURACIES OF THREE WAYS OF DETERMINING ANGULAR DIP AND STRIKE FROM TWO COMPONENTS.

Case.	Observed Values.			Derived Values.								Errors Referred to Computed Values.						Remarks.
				By Geometric Construction.						Computed Values.		In *A*.		In *B*.		In *C*.		
		Dips.		*A*.		*B*.		*C*.										
	θ	α	β	φ	δ	φ	δ	φ	δ	φ	δ	φ	δ	φ	δ	φ	δ	
				° ′	° ′	° ′	° ′	° ′	° ′	° ′	° ′	° ′	° ′	° ′	° ′	° ′	° ′	
1..	15°	2°	$2\frac{1}{2}$°	42 00	3 10	41 50	2 50	42 30	2 55	42 53	2 57	0 53	0 13	1 03	0 07	0 23	0 02	Unstable.
2..	30°	3°	10°	11 40	15 20	12 15	14 15	11 30	14 45	11 24	14 52	0 16	0 28	0 09	0 37	0 06	0 07	Fairly stable.
3..	60°	5°	20°	13 40	21 10	13 50	20 40	13 00	21 00	13 18	20 51	0 22	0 19	0 32	0 11	0 18	0 51	Stable.
4..	90°	2°	$2\frac{1}{2}$°	38 15	3 10	38 20	3 15	38 00	3 20	38 40	3 12	0 25	0 02	0 20	0 03	0 40	0 08	Stable.
5..	120°	3°	10°	12 30	13 35	12 50	13 35	12 45	13 30	12 39	13 28	0 09	0 07	0 11	0 07	0 06	0 02	Stable.
6..	150°	10°	12°	13 30	37 15	13 40	44 00	13 30	37 00	13 35	36 55	0 05	0 40	0 05	7 05	0 05	0 05	Fairly stable.
7..	165°	5°	20°	2 55	59 15	2 50	92°	2 30	[a]	2 53	60 05	0 02	0 50	0 03	32°	0 23	—	Unstable.

[a] Outside of diagram.

A. Values derived from geometric constructions on a 5-cm. radius using natural tangents of the dip angles.

B. Values derived from geometric constructions on a 5-cm. radius using the angles themselves in place of their tangents.

C. Values derived from the diagrams of Plate I. and Fig. 15.

Method.	Values of θ.	No. of Determinations in the Average.	In φ.	In δ.
Average error by *A*-method....	between 15° and 165°[b]	23	0° 16′	
Average error by *A*-method....	between 15° and 165°[b]	23		0° 17′
Average error by *B*-method....	between 30° and 150°	17	0° 17′	
Average error by *B*-method....	between 30° and 150°	14		0° 19′
Average error by *C*-method....	between 15° and 165°[b]	23	0° 14′	
Average error by *C*-method....	between 30° and 150°	17		0° 13′

[b] The error in dip by this method very rapidly increases for dips over 10° near the limits of this range of θ.

etc., etc. The units used for the gradients make no difference whatsoever in the results. One may therefore verify a result on these diagrams by multiplying or dividing the gradients by some convenient factor, say 10—though the same is true for any other factor—and re-solving the problem on the same diagram.

TABLE II.

SHOWING THE ACCORDANCE WITH THE TRUE VALUES WHICH MAY BE EXPECTED FROM SOLUTIONS BY THE DIAGRAMS.
DIPS IN TERMS OF GRADIENTS.

Case.	Observed Values.			Derived Values.				Error Referred to Computed Value.			Remarks.
	θ.	Gradients.		Diagram.		Computed.					
		A.	B.	φ.	$\triangle$.	φ.	$\triangle$.	φ.	$\triangle$.	%$\triangle$.	
1..	15°	20	25	43°	29	43° 23′	29.1	0° 23′	0.1	0.3	Unstable solution; near limits of diagram.
2..	30°	30	100	11½°	150	11° 27′	151	0° 03′	1	0.7	Not very stable solution.
3..	60°	50	200	13¾°	210	13° 55′	208	0° 10′	2	1.0	Stable solution.
4..	90°	264	335	38¼°	425	38° 14′	427	0° 01′	2	0.5	Stable solution.
5..	120°	42	113	15½°	160	15° 11′	158	0° 04′	2	1.3	Stable solution.
6..	150°	1,100	1,800	11¼°	5,625	11° 18′	5,612	0° 03′	13	0.2	Not very stable solution.
7..	165°	50	200	3°	1,000±	2° 59′	961	0° 01′	39±	4±	Unstable solution; extreme limits of diagram.

θ smaller than 30° or larger than 150°, as cases 1 and 7, should never be used in practice.

Average error of ϕ, omitting Cases 1 and 7 ..... 0° 04′.2

Average error in % δ, omitting Cases 1 and 7 ..... 0.8%

To compare the three methods of (*a*) descriptive geometry, (*b*) trigonometry, (*c*) diagram, the table (top p. 51) has been prepared to show the results by the three methods of the actual solutions of a variety of problems requiring dip and strike from two dip components. The rigid solution by trigonometry is taken as correct.[11] The others are compared with it.

We may therefore expect the accidental error in any of these graphic determinations (within the range for which it holds in the case of the *B*-method) to be of the order of ¼ to ⅓ of a degree.

It will be seen that for accuracy the odds are slightly in favor of the diagrams (on a scale about that of Plate I.) as against the descriptive geometry. It is reasonable to suppose, however, that the departure from the true values would be about the same in each from the printed plates and geometric constructions on a 5 cm. radius as used for these table. The geometric method has the advantage of being applicable anywhere with the simplest equipment; but in the office the diagrams would save much time. The difference in accuracy of the two methods, if there is any, is not of practical import, however; for the probable error of the ordinary field observation overshadows it considerably. The probable error by either method is well within that of any but the most refined field measurements. There is therefore no practical loss of accuracy in the use of descriptive geometry or diagram as compared with the rigid trigonometric solution.

[11] These computed results are to be taken as representations and not guarantees, however.

The Maples,
Claremont, Illinois.

A CONTRIBUTION TO THE GEOLOGY OF THE VIRGINIA EMERY DEPOSITS.[1]

THOMAS L. WATSON.

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INTRODUCTION.

Of the five chief commercial areas of emery, four—Greece and Turkey in Eurasia and New York and Virginia in the United States—are genetically associated with plutonic igneous intrusions. The fifth—Massachusetts in the United States—though somewhat more doubtful, may also be the result of igneous processes. Broadly interpreted, all except the Massachusetts deposits are probably of the contact-metamorphic type. Genetically they may be briefly summarized as follows:

The Grecian deposits on the island of Naxos[2] in the Grecian

[1] Presented by title before the Amherst meeting of the Society of Economic Geologists, December, 1921.

[2] Papavasiliou, S. A., *Zeitschr. Deutsch. Geol. Ges.*, Bd. 65, Abh., pp. 1–123, 1914.

Archipelago and the Turkish deposits near Smyrna in Asia-Minor are developed as lenses or pockets in crystalline limestones near granite intrusions and are more or less closely associated with granite pegmatites.

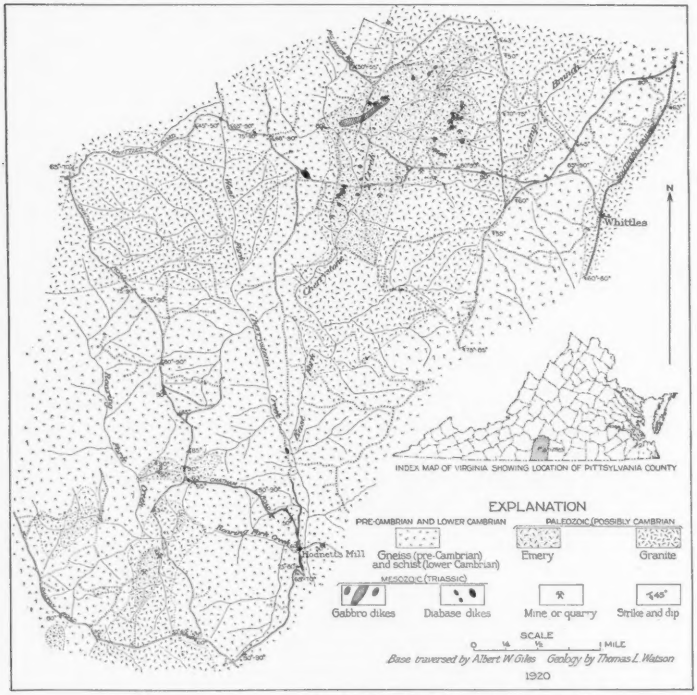

Fig. 17. Geologic Map of Emery Area in Pittsylvania Co., Virginia.

The Chester emery deposits in Hampden County, Massachusetts, have been traced for several miles in a narrow belt of foliated amphibolite contained in sericite schists of Silurian age. They are regarded by Emerson[3] as metamorphosed sediments and by Pratt[4] as igneous magmatic segregations. More recently

[3] Emerson, B. K., Mon. U. S. Geol. Survey, vol. 29, p. 145, 1898.
[4] Pratt, J. H., Bull. 269, U. S. Geol. Survey, 1906.

Gordon[5] has suggested that the deposits may owe their origin chiefly to the desilication of a granitic pegmatite. The ore is a granular mixture of magnetite and corundum, without spinel, and grades in places into almost pure magnetite.

The deposits of the Cortlandt area near Peekskill in Westchester County, New York, occur as veins, pockets, or lenses associated with norite and sillimanite schist and, according to Rogers,[6] have been formed by the absorption of schist (Manhattan) in the basic magma of the Cortlandt series. The emery has usually been referred to as an example of magmatic segregation, based probably on the investigations of Williams,[7] but the so-called magmatic segregations probably represent absorption of schist xenoliths by the basic norite magma. Some pure emery is reported but the bulk of the ore is a spinel emery.

The emery deposits near Whittles in Pittsylvania County, Virginian, the subject of the present paper, are probably contact-metamorphic deposits developed as lens-shaped bodies chiefly in schists but to some extent in granite near the schist-granite contact. The emery bodies occurring in the granite are similar in all respects to those found in the schists and are regarded as schist xenoliths absorbed by the granite magma. The ore is a spinel emery.

Mineralogically the emery of the four areas is of two distinct types: (1) true emery—a mixture of corundum and magnetite, with or without hematite derived from the magnetite; and (2) spinel emery—a mixture of spinel (pleonaste-hercynite), corundum, and magnetite. The Grecian, Turkish, and Massachusetts deposits are of the first type, while those of New York and Virginia are of the latter type.

The purpose of this paper is to summarize briefly some of the more important facts in the geology of the Virginia emery de-

[5] Gordon, S. G., *Proc. Phila. Acad. Nat. Sci.*, Part I., 1921, pp. 185–186.

[6] Rogers, G. S., N. Y. Acad. Sci., Anns., 1911, vol. 21, pp. 11–86.
Berkey, C. P., and Rice, M., N. Y. State Mus. Bull., Nos. 225, 226, 1921, p. 91.

[7] Williams, G. H., *Amer. Jour. Sci.*, 1887, vol. 33, pp. 135–144, 191–199, 243.

posits, which possess both considerable scientific interest and commercial importance. A report treating in detail the geology of the ore deposits will be issued shortly by the writer as a publication of the Virginia Geological Survey.

LOCATION OF AREA.

The Virginia emery area lies in the north-central part of Pittsylvania County on the west side of the Southern Railway, about 40 miles south of Lynchburg and 20 miles north of Danville (Fig. 17). The principal emery workings are within two miles of Whittles, the main shipping point on the Southern Railway. Small shipments from the southern part of the area have been made from Chatham, 5 miles south of Whittles.

GEOLOGY OF THE AREA.

As mapped by the Virginia Geological Survey, the area comprises approximately 20 square miles, but not all of this is emery-bearing. (See Fig. 17.) It forms a part of the crystalline rock complex of the Piedmont Plateau province, has an average elevation of about 800 feet above sea-level, and is characterized by the absence of marked relief. The rocks are deeply weathered, so that exposures of hard, fresh rock are infrequent—a condition which rendered accurate mapping difficult and in places uncertain.

Geologically the area is one of pronounced regional and igneous metamorphism. It is composed of an older crystalline metamorphic complex of schists and gneisses with thin bands of quartzite and, farther northwest, lenses of moderately coarse crystalline limestone (marble). This rock complex is injected in places by granite pegmatites and quartz veins, and by a series of younger intrusive igneous rocks, chiefly granite, gabbro, and diabase. The emery bodies occur both in the schist and in the granite (aplite-pegmatite), but always near the schist-granite contact.

Metamorphic Crystalline Rocks.

These include schists, gneisses, quartzites, and crystalline limestones. The emery deposits are intimately associated only with the schists and quartzites, hence they are of importance in this study.

The Schist-gneiss Complex.—This older rock complex probably forms five eighths of the area mapped, much the greater part of which is schist. It is essentially similar to the "Carolina Gneiss" mapped south of Virginia by the United States Geological Survey as pre-Cambrian in age. There is sufficient field evidence, however, within the area and beyond, for regarding the gneisses as pre-Cambrian in age and the schists not older than Cambrian, but their differentiation in many places is exceedingly difficult or impossible.

The gneisses are prevailingly biotite-bearing rocks, with or without intergrown muscovite. Garnet and sillimanite are sometimes present. Hornblende varieties are essentially absent but are known beyond the limits of the area. Indeed with one or two minor exceptions the rocks of the area, both igneous and metamorphic, are characterized by the practical absence of hornblende. The gneisses correspond to granites in mineral composition and are regarded as igneous in origin, the gneissic structure being secondary and not primary.

The schist series comprises a variety of types, the prevailing one of which is a muscovite-biotite bearing rock, frequently garnetiferous, and usually containing, besides quartz, some accessory feldspar, often much sillimanite, and at times microscopic crystals of tourmaline. It is with this variety of schist, altered by igneous metamorphism, that the more important commercial bodies of emery thus far worked are associated. The schists are sedimentary in origin, derived evidently by the anamorphism of chiefly argillaceous and arenaceous sediments. In the vicinity of the ore bodies the schists have been altered by igneous metamorphism, including injection in places by pegmatites and quartz veins.

Mica Schist and its Altered Contact Phase Compared.—Chemical analyses of the fresh mica schist and its altered contact meta-

morphic phase with which the emery bodies are chiefly associated are given in the table below.

TABLE I.

ANALYSES OF FRESH AND ALTERED SCHISTS, PITTSYLVANIA COUNTY, VIRGINIA, EMERY AREA.

	I.	II.
SiO_2	51.76	31.96
Al_2O_3	25.71	43.46
Fe_2O_3	1.66	7.08
FeO	7.73	9.07
MgO	2.21	4.62
CaO	1.32	.06
Na_2O	.91	.37
K_2O	5.73	
H_2O-	.25	.21
H_2O+	1.18	1.24
TiO_2	1.15	1.78
MnO	.04	.11
BaO	.51	....
P_2O_5	.11	.08
	100.27	100.04
Sp. G.	2.871	3.493

I. Fresh mica schist, Bennett barite mine near Toshes, Pittsylvania County, Virginia. (Penniman & Browne, analysts.)

II. Altered (contact metamorphic) schist near emery openings on Yeatts place, 1½ miles northwest of Whittles, Pittsylvania County, Virginia. (S. D. Gooch, analyst.)

The rock yielding the analysis in column I., Table I., is the dominant schist of the area. It is a dark gray, medium coarse-grained, foliated rock which shows in hand specimens the principal minerals biotite and muscovite and on cross fracture surfaces quartz and scant feldspar. Microscopically it is a sillimanite-bearing quartz-mica (biotite> muscovite) schist containing usually subordinate feldspar (microcline and oligoclase) and scant tourmaline, zircon, apatite, and pyrite.

Sillimanite is abundant in thin sections of the schist but can not be identified in hand specimens. It is plainly visible, however, in the altered contact phase of the rock represented by analysis

II., Table I. Thin sections of the fresh schist obtained at a depth of 150 feet just beyond the northwest limits of the mapped area show conclusively that the sillimanite is later than and developed from the principal minerals in the rock, especially the micas and more particularly biotite. All stages in the process of alteration are readily traced in the thin sections. It seems clear to the writer that the sillimanite is not a product of regional metamorphism, but has probably developed from the fluids of the granite magma reacting on the minerals of the schist. Its formation probably correlates in time, therefore, with that of the pegmatites which invade the schists and of the intimately associated emery bodies; the source of the material in each case being the invading fluids from the intrusive granite magma.

The contact-metamorphic phase of the schist described above and represented in analysis II., Table I., is entirely unlike the mica schist from which it has been derived by igneous metamorphism, both in general physical appearance and in composition. It is a tough slabby rock of dense aphanitic texture and dark gray color. Sillimanite is usually the only mineral that can be identified in hand specimens. Microscopically the rock is composed of a mixture of intergrown silicate and ore minerals. In order of abundance the principal silicate minerals are sillimanite, cordierite, andalusite, and biotite. The ore minerals include magnetite and green spinel which is identical with that of the emery bodies.

The analyses of the schists (Table I.) indicate losses of considerable potash and silica and some lime, while alumina, iron oxide, and magnesia have been added in notable amounts. These changes are clearly indicated in the mineral composition of the rocks as shown in their microscopic study summarized above.

Quartzite and Crystalline Limestone.—Thin bands of quartzite, interbedded with the schists in places and conforming in structure, form one and sometimes both walls of the emery bodies opened on the Yeatts place, 2 miles west-northwest of Whittles. The rock is closely jointed and frequently pegmatized. Occasionally there are noted small areas of tiny grains of black tourmaline

intergrown with the quartz. Microscopically the rock is composed almost entirely of interlocking grains of quartz. In every case thus far observed the contact between the emery bodies and quartzite is sharp and without evidence of gradation.

Several miles northwest of the area mapped in the vicinity of Toshes and Pittsville the schists are interbedded with lenses of crystalline white and pink marble with which commercial deposits of barite and magnetite are associated. Chemical analysis shows the rock to be a calcic marble low in magnesia, containing 91.07 per cent. of $CaCO_3$ and 3.73 per cent. of $MgCO_3$. No evidence has been found of the occurrence of carbonate rocks at any point within the emery area proper.

The quartzites and marbles are regarded as Lower Cambrian, the same age as the schists with which they are interbedded.

Igneous Rocks.

The igneous rocks within the area mapped include granite of several varietes, olivine norite, and diabase with or without olivine, all of which are intrusive into the schist-gneiss complex and are therefore younger. Granite pegmatites and quartz veins are also included here.

The basic rocks, norite and diabase, occur as dikes of Triassic age, and since they apparently have no relation to the emery deposits, which are regarded as older, they do not merit further consideration.

Granite.—Granite is much the most extensive of the igneous rocks intrusive into the older rock complex, and probably makes up approximately three eighths of the area mapped. It is not older than Cambrian in age and is cut by both the norite and diabase. Two distinct facies of the granite are recognized: (1) Biotite granite with or without muscovite, and even-granular to porphyritic in texture; and (2) muscovite-bearing dosodic aplite-pegmatite which contains in places small scales of biotite sparsely scattered through it. Of these two, the normal biotite granite is the more abundant. The emery bodies are genetically related to the aplite-pegmatite and occur both in it and in the schists but

always near the granite (aplite-pegmatite)-schist contact. Nowhere have the emery bodies been observed in such relations to the normal biotite granite, hence further description of the latter rock need not be given.

The aplite-pegmatite is a light-colored, nearly white muscovite-bearing granite characterized by the usual irregular textures of such rocks. Microscopically the rock consists of albite and orthoclase in varying proportions, quartz, subordinate muscovite, and in several thin sections scant biotite and an occasional colorless amphibole. The ore minerals composing the emery bodies have not been observed in any thin sections of either phase of the granite.

The chemical composition of the aplite-pegmatite (column I.) with which the emery bodies are associated and in some cases entirely enclosed, of pegmatite cutting one of the emery bodies enclosed in the aplite-pegmatite (column II.), and of the normal biotite granite (column III.) is shown in Table II.

TABLE II.

ANALYSES OF GRANITE, PITTSYLVANIA COUNTY, VIRGINIA, EMERY AREA.

	I.	II.	III.
SiO_2	75.29	76.84	69.35
Al_2O_3	15.47	14.78	16.57
Fe_2O_3	0.56	0.59	0.35
FeO	0.25	0.18	1.85
MgO	Tr.	Tr.	0.57
CaO	0.71	0.37	1.98
Na_2O	3.92	4.92	3.10
K_2O	3.03	1.50	5.21
H_2O-	0.07	0.04	0.07
H_2O+	1.00	0.94	0.38
TiO_2	0.02	0.03	0.28
P_2O_5	0.11	0.09	0.26
MnO	0.02	0.01	0.10
	100.45	100.29	100.07
Sp. G.	2.659	2.663	2.667

The analyses show the aplite-pegmatite (I.) and the pegmatite (II.) to be appreciably more silicic than the normal biotite granite (III.) I. and II. are dosodic rocks, while III. is sodi-potassic.

Pegmatites and Quartz Veins.—Granite pegmatites, which sometimes carry black tourmaline and red garnet, inject the gneiss-schist complex in places, including quartzite and crystalline limestone. They form "eyes," lenses, and narrow bodies developed both along and across the planes of foliation. The pegmatites are closely associated with the ore bodies and actually cut them in several places. Fig. 18 is a sketch of the face of an

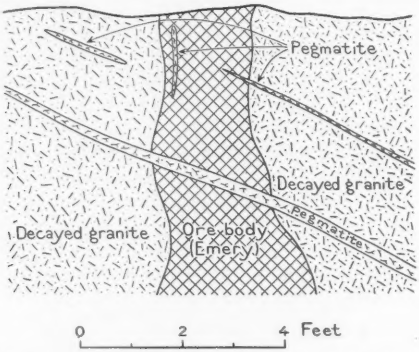

FIG. 18. Heading of emery cut in granite, J. D. Craddock's place, 2¼ miles west of Whittles. Shows emery body cut by pegmatite ½ to 3 inches thick.

emery body enclosed in the aplite-pegmatite and cut by narrow granite pegmatites which gradually fade into the enclosing aplite-pegmatite. A chemical analysis of this pegmatite is given in column II. of Table II. Microscopically it is composed of the principal minerals albite-oligoclase, orthoclase, quartz, biotite, and muscovite. Only a single instance has thus far been observed of the ore bodies developed in the schists and quartzite being cut by pegmatite. This is shown in an open cut recently made on the Yeatts place in decomposed schists, exposing an emery body cut by a granite pegmatite not exceeding 6 inches in width. Pegmatites that cut the emery bodies usually range from 1 to 3 inches in thickness and are frequently completely kaolinized. The wall rocks of the schist emery bodies, including both schists and quartzites, are often highly pegmatized, the dominant mineral

in which is feldspar now completely kaolinized to the depth of openings.

Cutting of the emery bodies by granite pegmatites has been observed thus far in only a few cases, relations that seem to be the exception rather than the rule. Both the ore bodies and the pegmatites originated from the same magma, the formation period of the pegmatites having continued beyond that of the ore.

Veins of quartz, which may carry in places subordinate minerals common to the pegmatites, are closely associated with the latter and with the ore bodies at the old emery openings on the Yeatts place, 1½ miles northwest of Whittles. Gradational phases between the quartz veins and pegmatites apparently exist, hence they are grouped with the pegmatites as end products of the granite magma, and were probably formed somewhat later than the emery bodies.

Structure and Metamorphism.

The metamorphic rocks of the region have the greater areal extent and have been developed by regional metamorphism under conditions of deep burial (anamorphism). They have been further altered in places by igneous contact metamorphism, and are freely injected in places, as described above, by granite pegmatites. The igneous rocks are usually massive, although partial foliated structure may be observed at times, especially in the granite.

Under anamorphic conditions the rocks have been rendered completely crystalline and strongly foliated. The schists so formed have been further changed in places about the granite contacts, resulting in greater densification, modification of structure, and development of new minerals. Further results of igneous metamorphism in the schists away from contact positions are shown microscopically by a marked development of sillimanite and to a much less extent tourmaline, their period of formation being coextensive with that of pegmatization and ore formation.

The strike of the foliation of the schist-gneiss complex is to the northeast, ranging between N. 10–85 degrees E., with a

probable average of N. 50 degrees E.; the dip is to the southeast, ranging from 40 degrees to vertical, with a probable average of 65 degrees. Except in the ore bodies and adjacent quartzites, jointing is not more strongly developed than in similar rocks in other parts of the Piedmont province. Definite evidence of faulting has not been observed; if developed it would be difficult to detect because of the extensive mantle of rock decay which usually conceals the fresh rocks.

THE ORE BODIES.

Types of Ore.

Two types of emery deposits based on the kinds of rocks with which the ore bodies are associated are recognized: (1) Schist ores, or those inclosed in schists or their weathered product, including thin bands of quartzite, and (2) granite ores, or those inclosed in the aplite-pegmatite. The ores are identical in composition and texture, but the schist ores in places exhibit a banding not yet observed in the granite ores. Also, coarse corundum has been noted only in the schist ores, but, as a rule, this constituent occurs as individuals of microscopic size in both types of ore.

Both types of deposits have been mined, but so far as developments have extended, the workable bodies in the schists are

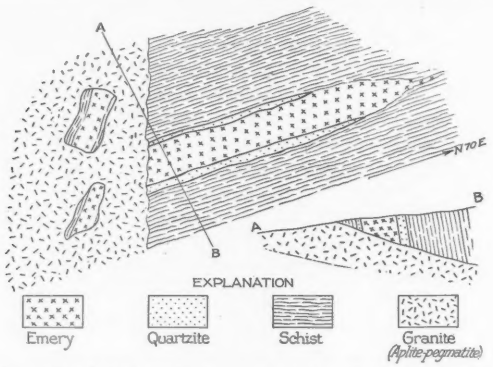

FIG. 19. Generalized sketch of plan and section illustrating mode of occurrence of the emery bodies. Section along line *AB* of plan.

usually larger in size, more tabular in form, and have been more extensively mined. In either case the emery bodies are located near the contact of the schists and aplite-pegmatite. Fig. 19 represents a generalized sketch of plan and vertical section, and will make clear this relation.

General Features.

It is necessary here to emphasize again the fact that weathering has progressed to an advanced stage, so that in all ore openings the rocks are entirely decomposed. Details of geological relationships therefore are more or less obscured and frequently difficult of accurate interpretation. The schists associated with the ores are usually thoroughly decomposed into vari-colored mottled clays, in which the rock structures may or may not be preserved; frequently they are not. Under such conditions the surfaces of the emery bodies are often coated with deep red clay. Quartzite, which forms one or both walls of the ore in some of the openings, is usually hard and fairly fresh, while the ore bodies which are more resistant to weathering afford, as a rule, only slight evidence of the effects of weathering.

From the developments thus far made in the area the emery bodies in the schists usually conform with the structure of the enclosing rocks, but in a few cases they cut across the foliation (Fig. 20). In the former case the ore bodies are rudely tabular

FIG. 20. Heading of emery cut in schists, Yeatts place, 1½ miles west-northwest of Whittles. Shows emery bodies (*b*) conformable with and cutting structure of decomposed schists (*a*).

in form, have steep southeast to vertical dips, and a probable average strike around N. 65 degrees E. The ore bodies which

cut the schist structure are more likely to be of irregular vein-like character. Likewise the emery bodies in the aplite-pegmatite are of somewhat similar form, although subject to considerable variation. They are probably smaller in most cases than the ore bodies in the schists. They probably represent xenoliths of the schist absorbed by the granite (aplite-pegmatite) magma.

So far as mining operations have extended, the largest ore bodies will measure up to 6 or 8 feet in width and more than 130 feet in length of solid emery. They do not preserve uniform thickness throughout, but narrow and widen at irregular short intervals. The depth to which they may extend can be conjectured only, since the maximum depth thus far reached in mining does not exceed 40 feet. It seems probable, however, that the individual ore bodies will not extend to great depth. They range from bodies of the sizes mentioned to thin stringers a small fraction of an inch in thickness interleaved with bands of similar thickness of the igneous metamorphosed schists. Microscopically the schist bands are composed of a mixture of intergrown silicate and ore minerals developed by contact metamorphism.

Except for a slight but variable thickness of chlorite which frequently partially encases the larger ore bodies, the contacts seem fairly sharp, especially in those cases where one or both walls are quartzite (Fig. 21). In such cases the quartzite is apt

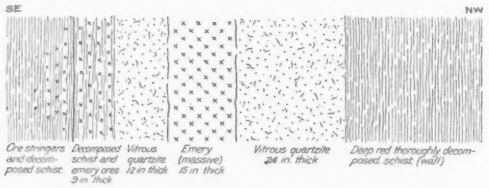
SE
NW
Ore stringers and decomposed schist
Decomposed schist and emery ores 3 in thick
Vitrous quartzite 12 in thick
Emery (massive) 15 in thick
Vitrous quartzite 24 in thick
Deep red thoroughly decomposed schist (wall)

FIG. 21. Heading of cut on Yeatts place, 2 miles west-northwest of Whittles. Shows relations of emery to quartzite and schist.

to be closely jointed, strongly pegmatized, and may carry some tourmaline. Both ore and quartzite may pinch and swell within short intervals along their strike. Where the contact is with

schist, gradation is more apparent; though usually not strongly marked megascopically, it is pronounced in thin sections. The granite ore bodies may be subject to considerable variation in themselves, but are sharply marked from the enclosing rock (aplite-pegmatite).

Associated Non-metallic Minerals.

These are few in number and are all silicates. They include, in the rich grade of ore, pale green chlorite and needles of sillimanite, the latter mineral being very scant as a rule, while the former may be more abundant but is almost entirely confined to the margins of the ore bodies. Thin sections of the contact rock near the ore bodies show a mixture of ore and silicate minerals, the latter including much sillimanite with some andalusite, cordierite, and biotite. Tourmaline is occasionally observed. Staurolite has been identified in the residual decayed product of the contact rock of the ore bodies in the aplite-pegmatite, and is developed in good crystals associated with red garnet near the granite-schist contact on the Craddock place. Sulphide minerals have not been observed.

Chlorite.—Except when in contact with quartzite, the emery bodies frequently show a marginal development of pale green scaly chlorite (probably corundophyllite) up to several inches thick, but as a rule much less. The chlorite may sometimes alternate with thin bands of the ore. Megascopic grains of the ore minerals, except corundum, are frequently sparingly intergrown with the chlorite, and in the thin sections studied, microscopic inclusions of the iron-bearing ore minerals are more or less abundant in the chlorite, so much so that it is difficult to separate an ore-free sample of the chlorite for chemical analysis. Chlorite sometimes forms veinlets in the emery enclosed in the aplite-pegmatite, which would seem to indicate that it was formed in part at least toward the close.

In the high-grade emery bodies the marginal development of chlorite is sometimes in irregular bunchy form, so that weathered surfaces of the ore frequently exhibit characteristic pitting, due

to removal of the less resistant chlorite. An important feature of the high-grade emery bodies is their practical freedom, except marginally, from micaceous (chloritic) minerals so common to the emery of many localities. In the lean ores chlorite may be distributed throughout the entire thickness of the emery body when it becomes the dominant constituent.

Structure of the Ore.

Most of the high-grade emery appears on casual examination to be entirely massive, cut by joints which break it into blocks of different sizes. More careful examination, however, reveals a more or less distinct banded structure due (1) to difference in texture (granularity), the bands having identical mineral composition (Plate III., *B*); (2) to segregation of light-colored corundum into tiny bands which alternate with thicker ones of the dark-colored minerals (Plate III., *A*); and (3) to thin bands of ore alternating with similar ones of silicate minerals. The first type of banding is the most frequent and is developed in both the schist and granite types of the emery, but is probably more frequent in the former. The second and third types of banding are developed only in the schist emery, and in both sharp folding is sometimes shown. Thus far the second type of banding appears to be rare and has been observed at only one locality.

Petrography of the Ore.[8]

The Virginia rock emery is a heavy black fine-grained crystalline aggregate which resembles somewhat closely fine-grained magnetite ore. It is an exceedingly tough rock and is magnetic due to the presence of magnetite. The texture is not entirely uniform, but, as described above, the difference in size of grain (granularity) of the component minerals even in hand specimens is frequently emphasized by sharp usually parallel boundaries which impart a banded appearance to the ore. In the coarsest textured emery the mineral grains do not exceed 2 mm. in diam-

[8] Watson, Thomas L., and Steiger, George, *Jour. Wash. Acad. Sci.*, vol. 8, No. 21, Dec., 1918, p. 669.

eter, while in the finer textured rock, which includes most of the ore, they are less than 0.1 mm.

In most of the emery the minerals are megascopically indistinguishable. Occasionally the schist ore contains corundum sufficiently coarse to be readily identified by the naked eye, developed generally either in small segregation-like areas or in thin light-colored bands or streaks (Plate III., *A* and *C*). The corundum crystals measure up to 2.5 cm. by 1 cm. wide, but probably most of them range from 1 to 3 mm. and under 1 mm. in size. They are usually nearly white to light grayish in color, less often light to deep blue.

Microscopic study of thin sections of the ore shows it to be a spinel-emery consisting of a fine-grained interlocking aggregate of spinel, magnetite, and corundum, with some ilmenite. The proportions of these may vary considerably. Some thin sections show the presence of a brown mineral which has been identified as probably högbomite. In addition to the ore minerals some thin sections show the silicate minerals sillimanite, andalusite (chiastolite), and a pale green chlorite (corundophyllite) to be present as microscopic accessories. Silicate minerals are usually lacking in the high-grade emery, except for chlorite developed marginally and scant sillimanite.

Spinel is the dominant mineral and usually makes up 50 per cent. or more of the rock. It occurs in rich green, sometimes brown, grains, that may show partial crystal outline. The spinel grains do not exceed 2 mm. in the coarser grained emery, and will average less than 0.05 mm. in the finer grained ore. Inclusions of magnetite and corundum occur, the former nearly always present either as plate-like films oriented with the octahedral cleavage or more abundantly as swarms of minute black dots usually confined to the central portion of the spinel grain, and frequently so abundant as to completely obscure the substance of the host. Some thin sections show an alteration product of a reddish brown, non-pleochroic, isotropic substance, probably högbomite, which forms distinct rims that contrast strongly with the unaltered rich green cores of the spinel.

TABLE III.

ANALYSES OF SPINEL FROM VIRGINIA AND NEW YORK.

	I.[9]	II.	III.
Al_2O_3	53.52	54.39	64.86
Fe_2O_3	10.35	10.52	
FeO	24.53	24.91	21.78
MgO	10.02	10.18	13.36
SiO_2	0.92		
TiO_2	0.67		
	100.01	100.00	100.00

I. Spinel from Pittsylvania County, Virginia, rock emery. George Steiger, analyst.

II. No. 1 calculated to a silica and titania free basis.

III. Spinel from Westchester County, New York, rock emery. G. Sherburne Rogers, *Ann. N. Y. Acad. Sci.*, vol. 21, p. 69, 1911.

A chemical analysis of the spinel is given in column I. of Table III. In column III. is given an analysis of the spinel of the New York emery for comparison. The analysis of the Virginia spinel corresponds to the formula $(Fe, Mg)O.(Al, Fe)_2O_3$ in which FeO is molecularly greater than MgO, and Fe_2O_3 is slightly more than one eighth of Al_2O_3. Compared with analyses of other spinels, the Virginia mineral is remarkable for its comparatively low MgO and high Fe_2O_3. If we assume only the compounds $MgO.Al_2O_3$, $FeO.Al_2O_3$, and $FeO.Fe_2O_3$ to be present, the composition of the Virginia and New York spinel, calculated from the chemical analyses (Table III.) in the usual way, may be expressed as follows:

	Virginia	New York
$MgO.Al_2O_3$	36.07	47.43
$FeO.Al_2O_3$	48.55	52.55
$FeO.Fe_2O_3$	15.31	....
	99.93	99.98

Reckoned in this way, the composition of the Virginia spinel

[9] Spinel and corundum were obtained as a residue after repeated treatment with strong hydrochloric acid. Corundum was determined separately and deducted.

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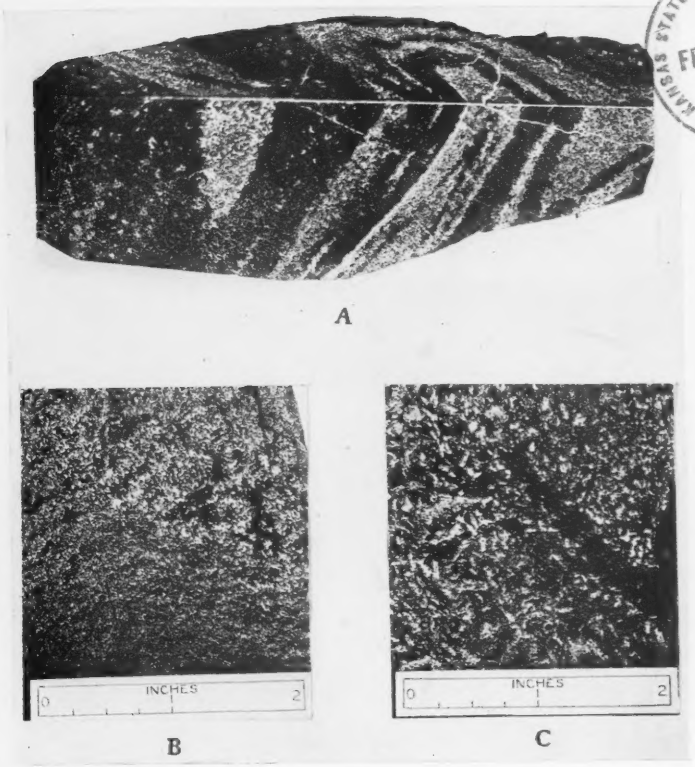

A. Polished specimen of emery ore showing plicated banding. Light bands corundum, dark bands spinel and magnetite.

B. Emery ore showing banding due to difference in granularity. Bands mineralogically identical. On'y two bands shown separated diagonally from upper left to lower right of figure.

C. Emery ore showing coarse corundum (white).

shows an excess of iron aluminate molecules (hercynite) over magnesium aluminate molecules (spinel proper), and may be regarded as intermediate between the two but more closely allied to hercynite. In the New York mineral hercynite and spinel molecules are more nearly equal, but the former are slightly in excess.

Magnetite, quantitatively, ranks next to spinel but is usually much less abundant. It is developed in grains which often show a strong tendency toward crystal outline, but good crystals are rare. The grains average slightly less in size than those of spinel with which they are intergrown and they are developed as inclusions in both the spinel and corundum.

Corundum is subject to wide variation in amount, failing entirely in some thin sections and present in large quantity in others. In the bulk sample of emery analyzed by Steiger,[10] corundum was estimated at about 18 per cent. It is developed both in grains and in distinct crystals of prismatic habit, which measure up to 0.12 mm. in length. It frequently cuts sharply against the spinel and magnetite, but the boundaries are sometimes irregular and somewhat indefinite, indicating simultaneous crystallization and the formation of intergrowths with the iron-bearing ore minerals. A part of the corundum, however, crystallized ahead of the spinel and magnetite. Inclusions of both spinel and magnetite occur, the latter being so abundant at times as to almost entirely obscure the corundum.

Chemical Composition.[11]

Chemical composition of the Virginia emery is shown in the analysis given in column I. Analyses II., of the Peekskill emery, New York, and III., of the Naxos emery, are tabulated for comparison.

[10] Watson, Thomas L., and Steiger, Geo., *Jour. Wash. Acad. Sci.*, vol. 8, No. 21, Dec., 1918, p. 674.

[11] *Ibid.*, p. 673.

TABLE IV.

ANALYSES OF EMERY FROM VIRGINIA, NEW YORK, AND GREECE (ISLAND OF NAXOS).

	I.	II.	III.
SiO_2	2.53	0.84	4.90
Al_2O_3	45.38	59.22	62.64
Fe_2O_3	23.33	16.66	29.61
FeO	17.90	14.02	1.80
MgO	5.71	3.54	0.06
CaO	0.06	Trace	0.45
Na_2O	0.20	Trace	
K_2O	None	Trace	
H_2O-	0.33	0.05	1.04
H_2O+	0.99	2.65	
TiO_2	3.72	3.28	
ZrO_2	None		
CO_2	0.07		
P_2O_5	None	Trace	
SO_3	None		
S	None	0.06	
Cr_2O_3	0.05	Trace	
NiO	0.04		
MnO	0.15	0.06	0.03
BaO	None		
SrO	None		
	100.46	100.38	100.53
Sp. G.	4.152[12]		4.008

I. Rock emery, 1½ miles west of Whittles, Pittsylvania County, Virginia. George Steiger, analyst.

II. Pure emery, Dalton mine, Westchester County, New York G. Sherburne Rogers, analyst. *Ann. N. Y. Acad. Sci.*, vol. 21, p. 64, 1911.

III. Naxischen handelssmirgels nach Oser. S. A. Papavasiliou, *Zeitschr. Deutsch. Geol. Ges.*, vol. 65, Abhl., p. 87, 1914.

The differences shown in the chemical composition of the emery from the three localities are due to variation in the proportion and composition of the minerals present in each. The Virginia and New York emery is a spinel emery, composed of a variable mixture of spinel, magnetite, corundum, and some ilmenite, with spinel usually the dominant constituent. The Naxos emery on the other hand is a mixture chiefly of magnetite and corundum, with little or no spinel or ilmenite. Higher total iron oxides and lower alumina characterize the Virginia emery. The

[12] Average of 5 determinations made by S. D. Gooch on separate fragments at 24° C.

very low magnesia content in the Naxos emery may be accounted for on the basis of the essential absence of spinel. The constituent in the emery from Virginia and New York is considered low for rocks in which spinel is the dominant mineral, but it can be accounted for on the basis of composition of the spinel, the analyses of which show FeO in excess molecularly of MgO. Ilmenite, not reported in the Naxos emery, accounts for the appreciable percentage of TiO_2 in the analyses of the emery from Virginia and New York.

Associated Mineral Deposits.

Near Pittsville and Toshes, 5 to 7 miles northwest of the Whittles emery area, are deposits of magnetite and brown iron ore (limonite), and of barite, each of which has been produced on a commercial scale. Here, as in the emery area, the dominant rocks are mica schists, of the same character, with in places thin bands of quartzite and thick lenses of coarse crystalline limestone, all of Lower Cambrian age. This series of metamorphic rocks is cut by granite pegmatites up to 40 feet in width.

The magnetite deposits are lens-shaped, somewhat tabular bodies lying between mica schist and crystalline limestone. They are probably the result of igneous metamorphism. Masses of intergrown garnet, green hornblende, and magnetite, and of garnet and quartz are observed in places on the surface. The garnet is red in color and an analysis shows it to be composed of a mixture of almandite and grossularite molecules, the former being predominant.

The brown iron ores (limonite) are residual deposits formed from weathering of certain members of the schist series. Thin sections show replacement of the rock minerals by iron oxide. Certain structural features in places suggest probable location along a fracture zone.

The barite represents replacement of crystalline limestone lenses in mica schists and their equivalent residual deposits derived by weathering of the former and associated rocks. Granite pegmatites cut the limestones and schists and recent field observa-

tions point to probable greater concentration of barium sulphate near the pegmatites. Along the northeastward extension of this belt of metamorphic rocks in the northern part of Pittsylvania County and the contiguous part of Campbell County, south of Lynchburg, are other important deposits of both barite and manganese.

Apart from the commercial importance of this greater area which comprises several mineralogic types of ore deposits, it is one of much scientific interest and importance in ore genesis.

Genesis of the Ore Deposits.

The scope of the present paper necessarily precludes more than a brief statement of the probable origin of the emery deposits. Thus far the ore bodies are found near the intrusive contact of granite (aplite-pegmatite) with mica schists, and in close association with granite pegmatites. They are developed both in schists that have been altered by igneous metamorphism of the contact type as evidenced by the characteristic assemblage of new minerals formed, and in granite (aplite-pegmatite), but always near the schist-granite contact. The general nature and composition of the ores strongly indicate that they represent metasomatic replacement deposits formed under conditions of high temperature and pressure. The emanations responsible for the formation of both the ores and the closely associated pegmatites were derived from the same granite magma, and were apparently formed at about the same time.

The ore bodies developed in the granite have probably resulted from absorption by the granite magma of schist xenoliths. Briefly summarized several of the more important reasons for this view are:

1. The composition of the emery including the associated rock minerals is similar to that of the schist. The rock minerals are invariably altered and the original minerals from which they were probably derived can only be surmised. Conditions surrounding the granite, as well as the schist type of ore, are greatly complicated because of profound weathering.

2. Shape and size of bodies are such as would be expected to develop from igneous metamorphism of schist xenoliths.

3. Nature of contacts. These are sharp and usually more or less angular; decidedly so in several cases. The conditions are not characteristic of segregation bodies in igneous rocks.

Age of the Deposits.

Evidence has been given for considering the emery deposits as being genetically related to the aplite-pegmatite phase of the granite intrusion. Also that the granites are definitely intrusive into and therefore younger than the schists with which the more important commercial bodies of emery are associated. The schist series including interbedded quartzites and marbles are regarded as Lower Cambrian in age, and are so represented on Fig. 17.

It seems reasonably certain that the ore bodies were formed at about the same time and from the same source as the granite pegmatites with which they are closely associated. Moreover the ores, as well as the pegmatites, were formed after the anamorphism of the schists, for both cut across the schist structure at times but are more often developed parallel to it. For these reasons the emery bodies, as well as the granite, can not be older than Cambrian and may possibly be younger. As indicated on the map, Fig. 17, both have been mapped provisionally as Cambrian in age.

ECONOMIC ASPECTS OF THE EMERY DEPOSITS.

From its weight and otherwise close physical resemblance to magnetite, the emery was first exploited many years ago for iron ore and later for abrasive material. The deposits, however, were not successfully worked until 1917, and up to the present time have yielded a large quantity of good material, derived partly from the extensive accumulation from weathering of loose fragments of ore of various sizes, which thickly littered the surface, and partly from openings of shallow depth. The major part of the production has come from the latter source.

The method employed in winning the ore is based on the

strongly developed joint structure in the emery bodies. After the enclosing rocks have been removed from around the ore bodies, the emery blocks of different sizes are dislodged by the use of iron bars forced into the joints, and then reduced to smaller size by the use of large hammers. Dynamite has been used only occasionally.

Tests made on the Virginia emery at the Bureau of Standards show it to be in every way the equal of Turkish emery and superior to the Peekskill, New York, emery. The Virginia area is a large one and should conditions warrant development of the deposits on a large scale, it is probably capable of yielding a large and steady production for some years. Probably the chief factor against development is the "freight rate from the southern part of the State to the emery-crushing mills in New York, Massachusetts, and Pennsylvania," which makes "it impossible to compete with the Turkish product, which reaches this country largely as ballast for light bulky cargoes." [13]

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[13] *Eng. and Mng. Jour.*, vol. 108, No. 3, July 19, 1919, p. 107.

PARAGENESIS OF THE ORES OF THE SILVER ISLET MINE, THUNDER BAY REGION, LAKE SUPERIOR.

CHARLES HENRY CHADBOURN.

INTRODUCTION.

The Silver Islet Mine develops a vein which crosses a small rocky islet in Lake Superior, about a mile off shore from Thunder Cape, Ontario, Canada.

The Silver Islet vein was discovered in 1868, and a small quantity of the ore was shipped during the summer of 1869. The vein was mined intermittently from this time until the fall of 1884, when operations were discontinued, due to a shortage of coal, and to a pinching-out of the ore in the vein. At this time the shaft had reached the 1,160-foot level, and had encountered two large bonanzas of native silver on the 300-foot and 400-foot levels. The original islet was 80 feet in diameter and had a maximum elevation of 10 feet above Lake Superior. The mine was partially dewatered during the summer of 1920.

GENERAL GEOLOGY AND VEIN CHARACTERISTICS.[1]

The ore body at Silver Islet[1] occurs in a divided vein 20 feet in width, which trends N. 35° W., and dips about 80° toward the northeast. The vein occupies a fault which cuts across a diabase dike, graphite-bearing aplite, and Animikie shales and graywackes. The dike is 300 feet thick and has an apparent strike of N. 59° E. and dip of 75° to the southeast. The Animikie sediments have a dip of 5° toward the east-southeast. The fault shows displacement, the northeast side having moved 8 feet toward the northwest. Horizontal striations could be seen in the slickensided country rock. The gangue of the vein consists of calcite, quartz, dolomite of varying shades of cream

[1] Descriptions taken from the *Transactions* Can. Min. Inst., vol. 23, 1920.

to pink, and ankerite. Graphite also occurs in considerable quantity and seems to be connected in some way with the occurrence of native silver.

PARAGENESIS OF THE ORES.

A short paper by A. L. Parsons and E. Thomson[2] might well be summarized at this time as the writer finds that his study of the paragenesis of the ores differs considerably with that disclosed in the above paper.

The writers concluded that macfarlanite and possibly animikite must be regarded as a mixture and not as a mineral species. The macfarlanite grains were found to be made up of silver, niccolite, galena, sphalerite, and chalcopyrite embedded principally in dolomite. The following sequence of deposition of the minerals was given: galena deposited contemporaneously with the sphalerite and followed by silver which is frequently entirely enclosed by niccolite, thus indicating that this latter mineral was the last metallic mineral to be deposited. Chalcopyrite is present in minute quantities and is associated principally with the sphalerite. Only one specimen of animikite was available for study. This was obtained from the dump and was black on the surface. The polished surface of this material showed silver, galena, and niccolite, which were apparently deposited in the order given.

The present writer agrees that macfarlanite and animikite are not a mineral species, but should rather be regarded as mixtures. However, he has concluded that the order of the formation of the metallic minerals is as follows: niccolite, sphalerite and chalcopyrite, galena, native silver (dycrasite ?), and argentite.

RELATIONS OF METALLIC MINERALS.

The niccolite is generally disseminated through the gangue in more or less dendritic masses. The niccolite also has a tendency to form rings or cores about the gangue; native silver replaces the niccolite.

[2] "Animikite and Macfarlanite from Silver Islet, Thunder Bay, Lake Superior," Contributions to Canadian Mineralogy, 1921.

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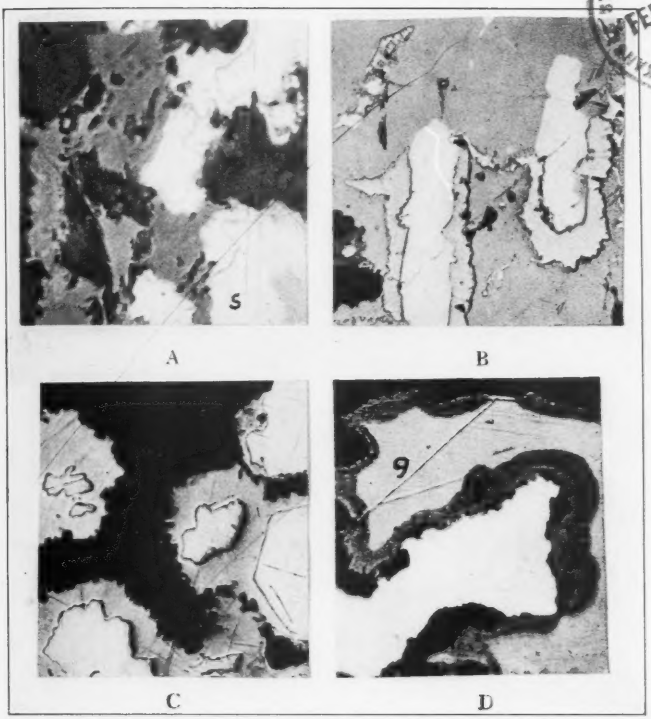

a. Sphalerite (gray) replacing niccolite (white). Native silver (*S*) replacing sphalerite and niccolite, gangue (dark gray). ×96.

b. Galena (gray) replacing niccolite (cream color), and native silver (white) replacing galena and niccolite, gangue (black). ×96.

c. Native silver (*S*) replacing niccolite, gangue (black) dolomite. ×96.

d. Argentite (*a*) replacing galena (*g*) and calcite (black). Native silver (white) replacing calcite and argentite. ×135.

The chalcopyrite and sphalerite are contemporaneous in their formation, the chalcopyrite occurring in rather negligible quantities in the ore, but where found is always associated with the sphalerite. Both of these minerals are replaced by galena, but apparently the chalcopyrite is much more easily replaced than the sphalerite, so that only small residual masses of the chalcopyrite are found.

Galena is the most abundant mineral in the ore specimens examined. Contrary to usual appearances the galena has a definite purple color, which apparently is not due to any intergrowth with the native silver. It replaces the niccolite, sphalerite, chalcopyrite, and is replaced by native silver and argentite.

The native silver and possibly some dycrasite is the most important of the metallics, being found in large amounts in various parts of the vein. There is without doubt little of the silver that approaches typical dycrasite in composition; some of it, however, gives a positive reaction for KCN, slowly etching differentially, corresponding to the microchemical tests in Davy-Farnham, "Microscopic Examination of the Ore Minerals." Some of the silver was also heated on plaster tablet with bismuth flux and gave an orange coating. Parsons and Thomson have reported the presence of antimony in the ores of Silver Islet, and assumed the presence of breithauptite. No evidence of the presence of this latter mineral was found, and the writer believes that part of this antimony must be assigned to dycrasite or antimonial silver.

The native silver replaces the gangue, sphalerite and galena. The replacement of niccolite by native silver is similar to that which has taken place in the silver veins of Cobalt, Ontario. In that district the native silver occurs as fillings of fractures in smaltite and niccolite and as replacements of the niccolite. A more detailed description of the replacement of niccolite by native silver will be presented under the heading of "Replacement Processes."

The argentite was found in appreciable amounts in only one of the specimens, as a peripheral replacement about the galena.

This band of argentite would naturally lead one to assume that the argentite might be of a distinctly later period, possibly due to secondary enrichment of the upper portions of the silver vein. This problem would necessarily be difficult to solve as the specimens were not labelled as to their location in the vein. The relative age of the argentite and native silver is not quite certain.

REPLACEMENT PROCESSES.

The most common type of replacement which is encountered in the study of these ores is the replacement of the niccolite by sphalerite, galena, and native silver. The replacement by the last two has been more extensive than that by the sphalerite. The niccolite is found as residual masses in the galena, and replacement has evidently taken place from the outer margins of the niccolite grains towards their centers.

The introduction of the chalcopyrite, sphalerite, and galena in all probability followed closely the niccolite deposition, so that the introduction of these four minerals may be considered as constituting a single phase of mineralization of the hypogene solutions.

The replacement of the niccolite, sphalerite and galena by the native silver is to the writer a distinctly later phase of the hypogene mineralization. Following the earlier stage of mineralization, there was no doubt a slight fracturing of the vein, thus giving ready access to the ascending silver solutions. A secondary enrichment of the silver was brought about by erosion of the upper portions of the vein, the native silver being deposited at successively lower levels as the erosion continued. The writer bases his conclusions on the following facts: the large ore bodies occurred in the upper portions of the vein; these bodies were broad near the surface but tapered downward; the native silver was deposited in the cleavage planes of the earlier minerals and as replacements of these minerals.

The native silver has replaced the niccolite to a greater extent than it has the sphalerite or galena, which is possibly due to the

fact that silver solutions attack niccolite more readily than galena. The replacement of the galena by the native silver has in nearly every instance taken place from the center of the galena grains outward, thereby differing from the more general mode of replacement which takes place from the outer margins towards the center of the minerals. The native silver was found in some specimens, replacing the central portions of the galena and continuing into and replacing the niccolite grains. This replacement appears to have taken place along almost parallel planes as if the silver solutions had followed along minute fractures and replaced the niccolite and galena along these fractures (Plate IV., *b*). The most of the specimens, however, show the native silver replacing the niccolite, irrespective of any parallel arrangement of the niccolite grains, and thus of any definite fracture planes. All gradations in the replacement of the niccolite by the native silver, from the initial entrance of the native silver as small cores in the niccolite to the final almost complete replacement in which the niccolite remains as a thin shell about the native silver (see Plate IV., *c*).

SUMMARY.

The order of the paragenesis of the minerals is as follows: (1) Gangue; (2) niccolite; (3) sphalerite, chalcopyrite; (4) galena; (5) calcite; (6) native silver and argentite. The niccolite was without doubt the first mineral deposited, followed closely by the sphalerite, chalcopyrite and galena. Of these four minerals the galena was the last deposited, having replaced the other three and especially the sphalerite to a very marked degree. The native silver and argentite are of a distinctly later phase in the hypogene mineralization of the vein. The native silver replaces all of the above-mentioned minerals with the exception of the argentite, which forms a peripheral replacement about the galena. The relative age of the native silver and argentite is not quite certain. The primary native silver was derived from ascending solutions, but was subsequently enriched at lower levels by the erosion of the upper portions of the vein. This order of

formation compares well with that of Cobalt, Ontario. The following order of sequence in that district was given by H. V. Ellsworth,[3] and others,[4] as follows: (1) Arsenides; (2) calcite followed by fracturing; (3) deposition of native silver and argentite.

[3] Ontario Bureau of Mines, 1916, vol. 25, Pt. 1.

[4] E. S. Bastin, Economic Geology, vol. 12, 1917, pp. 219–236. W. L. Whitehead, Economic Geology, vol. 15, 1920, pp. 103–135.

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EDITORIAL

COÖPERATION IN GEOLOGY.

A GENERATION ago, geological study and research was confined almost wholly to colleges and universities and to state and federal surveys. The economic geologist, except when working through such agencies on broad problems of the development of natural resources, did not exist. Application of geology to the problems of mining was left to the mining engineer, with his rudimentary training in the science, to an occasional commission for some university man to study a particular problem, or to such information as might be secured from consultation with a survey geologist. There were not more than enough geologists engaged in strictly economic work, as we understand it today, to furnish the exceptions which are said to prove the rule.

Today considerably more than half quantitatively of the geological work, in the Americas at least, is being carried on by economic geologists; by trained experts giving their best effort and thought, at the expense of clients expecting to profit from such services, to the problems of discovery and effective utilization of various minerals. Nor does economic work suffer by qualitative comparison with the work of the older groups. Geological surveys as aids to metal, coal, and petroleum mining operations are often executed over wide areas with a degree of detail but seldom obtainable by public surveys because of prohibitive expense.

It is true that much commercial work, particularly in petroleum geology, is done by men who may not have had such broad training nor so wide experience in geology as could be desired but it may be remembered that they are trained specialists in their work. A so-called "rock hound" working in Oklahoma, for example, is able to map detailed structure in the gently folded Pennsylvanian rocks of that state with a degree of precision not surpassed by any other geologist, no matter how broad his experience, and a young geologist whose professional life has been

spent in the office study of well logs and cuttings may be able to give valuable information on sedimentation to our leaders in the study of that phase of our science.

Commercial geological work must not be judged by the standards set for public surveys or strictly scientific work. It is done for a specific purpose and to meet certain standards and can not be gauged by other standards. As has been said elsewhere, a petroleum geologist working in a fairly well-known region is no more to be censured for failing to note or collect from an important fossil locality than a paleontologist should be blamed for failing to note an anticline while working in the same region.

If the extent and value of geological work done for economic purposes be recognized, then it is of utmost importance that steps be taken to add the results of such work to the common fund of fact and theory upon which the science of geology is based.

This making available of the geological results of economic work is accomplished by direct publication, by gift of unpublished data to public surveys or research geologists, and by interchange of information resulting from contact between economic geologists and geologists engaged in more purely scientific work.

Much is being accomplished by direct publication but much more could and should be accomplished in this direction. Publication should be regarded as an obligation which economic geologists owe to the general science; a debt which should be discharged as soon as the exigencies of economic demands permit.

Non-publication is generally blamed upon refusal of clients to permit publication but it is actually and generally due to procrastination or laziness on the part of the geologist. Most clients, when the feeling that they are giving away something which has cost them money can be overcome, are liberal with regard to publication and more of them would probably be so if geologists would go to the trouble of securing consideration of such results as might follow publication.

The field which seems to offer greatest present opportunity, however, is that of coöperation between state and federal surveys and economic geologists. These public surveys are the only agencies which can bring together and correlate much scattered

work done for economic purposes and secure its publication. Doubtless more is being done in this direction today than is generally recognized but there are still surveys which are either unaware of the very considerable possibilities of this nature or else are unable to take advantage of them because of lack of funds. No survey geologist, with the limited time at his disposal for the study of a single region, can afford to neglect any opportunity to acquire either fact or theory from economic geologists who have worked in the same region. They have given months or perhaps years of study to areas to which he can only give days. More can be done by surveys in certain regions in securing, checking, and correlating the very considerable available results of economic work than can be accomplished by original investigations and all of this work possible should be done now. The refusal, during the past few years, of an important state survey to attempt to correlate the results of the most detailed structural work over a wide area, offered conditionally to them by an active group of economic geologists, lost to the science, for the time at least, geological information of great value which will not be duplicated for years and then only at the expenditure of thousands of dollars.

On the other hand, economic geologists should take a much more active interest in assisting public surveys to secure appropriations and in their programs for work. Instead of accepting the occasional report which falls from the press as manna from Heaven, why not help the surveys to get necessary funds for work and why not develop, through societies and associations, some considered opinion as to work which ought to be done and make such opinion known to the administrative heads of the surveys within whose province the work lies? Surveys, state and federal, secure their appropriations from legislators almost wholly on the basis of the economic application of the results they obtain. The results of these surveys are offered directly to the public through publication but their interpretation and application lies generally in the hands of geologists engaged in economic work. It is eminently reasonable therefore that economic geologists should become articulate as to the type of work required and

regions where it should be done and that they should give every possible assistance toward making such work possible.

Unfortunately, from the general viewpoint, the present tendency in economic work is toward greater specialization and too little is done by geologists to break through the water-tight compartments which such specialization tends to build. One of the largest and most active geological societies, the American Association of Petroleum Geologists, is most actively engaged in the advancement of our knowledge of the geology of petroleum and in the advancement of geology as a science, yet it is doubtful whether its members are generally acquainted with the programs and publications of the Geological Society of America. The members of the older society are probably even less aware of the notable work of the Association. It is a pity that geology does not enjoy the benefit of more contact between these two organizations. Much mutual profit would result from occasional joint meetings of these two societies and there is no member of either society who might not profit from attending a meeting of the other society.

These three suggested methods for securing the results of geological work done for economic purposes before they are lost through non-publication may be termed, if we may borrow from the terminology of the industry of gasoline production, direct production, the compression method, and the absorption method. Direct publication is of course direct production, an old and well-tried method which is effective now and should be encouraged. Production through coöperation between groups of economic geologists and existing surveys may well be termed the compression method. It has great possibilities and pressure will be required from both sides to secure results. Production through better contact between economic geologists and geologists engaged in other work is essentially an absorption method. The last is the only method which will yield the ultimate residue of valuable products and is a method which may be profitably used even after economic work has been subjected to the searchings of the first two methods.

E. De Golyer.

DISCUSSION AND INFORMAL COMMUNICATIONS

SUPERGENE PROCESSES AT NEIHART, MONTANA.

Sir: In his paper under this title in a recent number of ECONOMIC GEOLOGY, Mr. Hurst comes to the conclusion, as the result of microscopic studies, that some of the polybasite in the ores of Neihart is hypogene, or primary, in origin. With this conclusion I should be inclined to agree. But if the relations depicted in Plate V. of Mr. Hurst's article are typical for the ores, the reasoning by which his conclusion was reached appears to me to be open to question. These criticisms are, however, offered with some hesitancy because of the realization that a halftone may not accurately and completely depict all of the relationships shown by the polished specimen, and with apologies in advance for any misconceptions due to this cause.

In Plate V., quartz with sharply defined crystal outlines is in contact with an association of sphalerite, galena, and chalcopyrite. The statement is made that these are "sulphides replacing quartz." It is not clear how such replacement could take place without destroying the straight crystal outlines of the quartz.

A similar criticism appears to be applicable to Plate V., *C*, which is labelled "polybasite replacing galena; both replacing sphalerite." The sphalerite seems to possess crystal faces suggesting that it has not been replaced by the bordering minerals. If both polybasite and galena have replaced sphalerite, replacement took place simultaneously and at the same rate, for straight edges of sphalerite are, at one point, in contact with galena, and at another, with polybasite. Yet the statement is made that galena and polybasite are *not* contemporaneous, but that the polybasite has replaced galena. The present writer would interpret Plate V., *B*

and *C*, as showing no evidence of replacement of either quartz or sphalerite. The polybasite shown in Plate V., *C*, and *D*, is interpreted as a replacement of galena, yet from these illustrations it is not clear why the two minerals may not be interpreted as contemporaneous. The statement (page 385), that "the masses of polybasite are scattered with extreme irregularity through the galena, they possess no crystal form, and seem to be entirely independent of such structural features as cleavage directions or planes of contact between the various minerals" is more suggestive of contemporaneity than of replacement. Contemporaneity, if demonstrated, would constitute evidence of hypogene or primary origin, whereas replacement would not.

Opposite interpretations from the same set of facts clearly raise two questions applicable particularly to the interpretation of microscopic relations: (1) What criteria are to be used to determine whether two minerals in contact are of the same or different ages, and (2) in the case of minerals that may be either hypogene or supergene, what criteria can be used to determine which class they belong to?

Without attempting an exhaustive discussion, it may be useful to seek a partial answer to these questions.

Diversity in age of minerals that are in contact may be shown by:

(*a*) Evidence that one mineral has filled open spaces in or alongside another,—fracture fillings, etc.

(*b*) Evidences of replacement.

(*c*) Incongruity in mineral composition. If the minerals in contact are known to form only under quite dissimilar conditions, it is clear that they are of diverse ages. Malachite and copper pitch ore, which form only in the oxidized zone, if in contact with chalcopyrite, which never forms in the oxidized zone, would exemplify this criterion. Only seldom is it necessary to appeal to this criterion alone. Usually it is used in conjunction with (*a*) or (*b*).

Of these criteria, evidences of replacement are the only ones we need consider. They are fairly well understood and include the following:

(*a*) Distribution of a mineral near what would obviously be channels along which mineral-bearing solutions could penetrate most readily, *i.e.,* along contacts between mineral grains, along mineral cleavages, partings and irregular fractures. Even when a relationship between the replacing mineral and such structural and textural features is not at first apparent, close scrutiny under high magnification will commonly show that this exists. Cf. many fine-grained associations of chalcocite and bornite, etc.

(*b*) Exceedingly ragged contacts between minerals, irregular even under high magnifications. These are especially significant; when enclosed by mineral *b* there are "islands" or outliers of mineral a, with the same crystallographic orientation as the adjacent "mainland" of *a*.

(*c*) Significance of crystal faces as mineral boundaries. It is axiomatic that a mineral which shows perfectly developed crystal faces characteristic of its own species can not have been replaced by the minerals with which it is in contact. It may, however, have itself replaced these minerals, for it is well known that certain minerals developed by replacement tend to assume their own characteristic crystal forms. Cubes of pyrite developed by the replacement of the wall rock minerals of veins constitute a familiar example. Quartz developed by replacement also shows a strong tendency to develop its characteristic crystal forms. Irregularity, though often developed, is therefore not an essential feature of replacement contacts. Why some replacing minerals should eat irregularly into the replacing minerals while others develop perfect crystal outlines is still obscure.

There remains to be considered the criteria for differentiating hypogene ore minerals, or those deposited by ascending solutions coming from a deep-seated source, from supergene minerals, or those deposited by descending solutions of meteoric origin, especially in the case of those mineral species which may be either hypogene or supergene.

In any ore it is often possible to state with assurance that certain of the minerals, usually common sulphides and gangue minerals, are hypogene. If a mineral whose origin is in question

is in contact with such minerals and shows no evidence of having replaced them or filled openings in them, this forms the strongest line of evidence of hypogene origin. Contemporaneous intergrowth with undoubted hypogene minerals is therefore the first and best criterion of hypogene origin.

Some minerals, however, may be a late hypogene replacement of earlier hypogene minerals. How shall we differentiate such replacements from supergene replacements? In general, it has been the writer's experience that most of the criteria of replacement already outlined, such as a distribution of the replacing mineral along and near contacts between mineral grains, along cleavages, partings, etc., apply equally to hypogene and supergene replacements. In many instances differentiation between hypogene and supergene replacements will be impossible, but in other instances it can be made. Composition becomes in some cases a criterion, for it is well known that certain minerals are invariably hypogene while others are formed only in the zone of sulphide enrichment or in the oxidized zone, and are therefore supergene. The replacement of chalcocite by malachite, for example, can only be interpreted as a supergene replacement, whereas a replacement of galena by the alloy of gold and silver electrum—observed by the writer in the ores of Tonopah—is interpreted as hypogene, since under near-surface conditions gold and silver are well known to part company.

The principle that many elements part company under near-surface conditions of oxidation and enrichment that are common associates under the conditions of hypogene mineralization is capable of further application. Under supergene conditions the replacement of one mineral by a second mineral is probably the commonest type of replacement noted. The second mineral may later be replaced by a third and so on. Frequently a series of replacements is noted involving progressive and consistent changes in chemical composition. Primary chalcopyrite, for example, may be surrounded by succeeding replacement rims of bornite, covellite and chalcocite in the order named—which signifies progressive removal of iron and sulphur and addition of copper.

Such seriatim replacements are rarely developed during hypogene mineralization. In a few instances simultaneous supergene replacements of one mineral by two minerals may be observed, but in general these are rare. In hypogene mineralization, on the contrary, simultaneous replacements of one mineral by a group of minerals is fairly common. Familiar instances of such phenomena on a large scale are afforded by the replacement of limestone by an aggregate of base-metal sulphides and gangue minerals, as, for example, in the primary ores at Leadville and at Aspen. On a small scale, such replacements are well shown in some of the Tonopah, Nev., ores, in the replacement of galena by a contemporaneous aggregate of carbonate, argentite, polybasite, electrum and chalcopyrite.[1]

Whatever may be the genesis of the silver minerals at Neihart —and it may well be that they are in part hypogene—evidence is gradually accumulating that some of the richest silver ores have been deposited from ascending solutions of deep-seated origin. The recognition of the process of downward enrichment by S. F. Emmons and Walter Harvey Weed, and its elaboration by many later investigators, was one of the great achievements in economic geology during the last generation. It is not surprising and entirely forgivable that, in their enthusiasm for a newly recognized principle, geologists should have pushed its application too far. Indeed, only the recent development of microscopic methods for the study of ores has made it possible, in many instances, to discriminate between hypogene and supergene processes in ore deposition. The importance of downward enrichment has become firmly established in numerous instances, especially in copper deposits, and in some silver deposits as well. Recently, however, evidence has been accumulated which shows that in many silver deposits downward enrichment is restricted to a very superficial zone and that mining below this zone is in ores which, though rich, are wholly or mainly hypogene in origin. This is the case apparently with the important gold-silver ores of Tono-

[1] Edson S. Bastin and Francis B. Laney, "The Genesis of the Ores at Tonopah, Nevada," Prof. Paper 104, U. S. Geol. Survey, 1918, pp. 23 and 24 and Plate IX., *A*.

pah, Nev.,[2] and with those of the great Comstock lode not far distant.[3] In many of the veins of the San Juan mountain region in Colorado[4] rich silver ores can be shown to be hypogene. Examination under the microscope has shown, for example, that much of the rich ore of the Smuggler Union-Humboldt vein is hypogene. Recently the life of the Smuggler Union mine has, I understand, been much extended by the discovery of a vein which did not outcrop, but which was very rich in silver minerals, and obviously these minerals cannot be supergene.

The native silver of the famous silver deposits of Cobalt, Ontario, which is clearly younger than the cobalt and nickel minerals with which it is associated, and is a replacement of them, was interpreted by S. F. Emmons and C. H. Van Hise as supergene—a product of downward enrichment. This view the writer was at first inclined to share, but the field work of W. G. Miller[5] and of W. L. Whitehead[6] has shown the existence of blind veins without outcrops which are exceedingly rich in native silver. Obviously such silver can not be supergene. Recently the present writer has shown that in the Cobalt ores native silver has in places been deposited contemporaneously with calcite, presumably by carbonate solutions of late hypogene origin. Further he has shown[7] that the arsenides and antimonides of cobalt and nickel are capable of precipitating metallic silver from solutions of silver bicarbonate. The hypogene origin of most if not all of the native silver at Cobalt, Ontario, seems therefore to be fairly well established.

The practical importance of a lessened emphasis on downward

[2] *Ibid.*, p. 47.

[3] E. S. Bastin, "Bonanza Ores of the Comstock Lode, Virginia City, Nev.," Bull. 735-*C*, U. S. Geol. Survey, 1922.

[4] E. S. Bastin, "Silver Enrichment in the San Juan Mountains, Colorado," Bull. 735-*D*, U. S. Geol. Survey, 1922.

[5] W. G. Miller, "The Cobalt-Nickel Arsenides and Silver Deposits of Temiskaming, Ontario," Bur. of Mines Report, vol. 19, pt. 2, 1913.

[6] W. L. Whitehead, "The Veins of Cobalt, Ontario," Economic Geology, vol. 15, pp. 103–35, 1920.

[7] E. S. Bastin, "Primary Native Silver Ores near Wickenburg, Arizona, and their Bearing on the Genesis of the Silver Ores of Cobalt, Ontario," Bull. 735-*E*, U. S. Geol. Survey, 1922.

enrichment in silver ores lies in the encouragement which it offers to deeper mining. Judgment as to the probable success of deep mining in veins rich in silver near the surface should not be prejudiced by preconceived ideas of the importance of downward enrichment. Each district and, in some districts, each mine presents a special problem, and the methods of microscopic studies of ores worked out in recent years offer one means of determining the relative importance of hypogene and supergene processes in the formation of the silver ores far in advance of the ultimate test by actual development. Moreover the practical value of information gained by such means is out of all proportion to the moderate cost at which it may be obtained.

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REFLECTED BURIED HILLS AND PETROLEUM GEOLOGY.

Sir: The most accurate compilation of data yet attempted, having a direct bearing on the existence and economic importance of the Nemaha Mountains, is embodied in Dr. Sidney Powers' contribution to ECONOMIC GEOLOGY, Vol. XVII., No. 4, June–July, 1922.

These mountains have been a subject for considerable study among mid-continent geologists since their occurrence is closely associated with oil accumulation in South Central Kansas. The northern extension of the range, however, has received less attention on account of the failure to find oil, where drilling has been done, and because of the heavy mantle of glacial drift and loess. Sufficient exposures of limestone and shale can be found along the major streams to determine satisfactorily the structure and stratigraphy of the region south of the Platte, but north of the river a practically unbroken covering of loess conceals all the strata involved in the folding which represents the northern extension of the "Granite Ridge," or Nemaha Mountains.

Very little can be added to that part of Dr. Powers' paper regarding Kansas, and it is the desire of the writer only to supple-

ment the original article by adding data relative to Nebraska, which were collected at various times between 1910 and 1916.

The presence of the "Granite Ridge" in Nebraska is proved by two wells, one near Dubois and one near Table Rock, Pawnee County. The type of folding which marks this ridge in Kansas and Pawnee County, Nebraska, and may be taken as a criterion of the presence of the ridge, can be found extending northward from Dubois, on the Kansas-Nebraska line, to a point two miles west of Oreapolis, a village on the Platte River a few miles west of Plattsmouth. Where it is possible to measure the amount of reverse (east) dip, a reversal of about 200 feet is found. This occurs in a distance of about two miles, but a much lower dip continues from four to six miles beyond the area of sharp folding. The fold at Oreapolis indicates a flattening of the ridge and a record of drilling in the vicinity of Omaha confirms the writer's opinion that the "Ridge" descends to the north and merges with the comparatively level pre-Pennsylvanian plain.

Contrary to Dr. Powers' statement that the granite ridge dips steeply to the north in Pawnee County, a detailed survey shows a north dip of 20 feet per mile in northeastern Pawnee County and slightly less than 15 feet per mile across western Nemaha County. An interval of approximately 400 feet exists between the Burlingame limestone which is exposed as surface rock at Dubois, and the Nebraska representative of the Cottonwood Limestone, which is at the surface in Western Nemaha County, near the village of Johnson. This indicates a northerly component in the dip of the strata of approximately 15 feet per mile. So far as is possible to determine, there are only minor variations from this.

The fold which undoubtedly represents this ridge in Nemaha and Otoe Counties is crossed by a broad, shallow east-west syncline, having its flat trough, roughly, in the drainage basin of the Little Nemaha River.

The "Ridge" in northern Otoe and southern Cass County is so completely covered with drift and alluvium that its exact location and nature cannot be determined. However, an examination of strata exposed some ten or twelve miles eastward, along

the Missouri River (in 21—10 N. 14 E.—S. dip 180 feet per mile), furnishes a reliable clue to the general behavior of the ridge itself.

These data, coupled with the presence of the Nebraska equivalent of the Lawrence shale of Kansas which is exposed in the Valley of Weeping Water Creek, west of Nehawka, show that the "Ridge" is again rising to the north and at the rate of more than 100 feet per mile. The geologic horizon exposed in the valley of Weeping Water Creek is nearly 800 feet lower in the column than the surface rock in the Little Nemaha basin, from which syncline the ridge rises so rapidly to the north. The surface rock (Burlingame Limestone of Kansas) at Dubois is approximately 400 feet lower in the column than the limestones prevalent in the Little Nemaha basin, and 400 feet above the shales found at Nehawka, in Cass County.

The village of Nehawka is located squarely in the region of sharp easterly dip, but the structural "high" is between Nehawka and Weeping Water. There is a southerly component of about 30 feet per mile in the dip of the beds south of Nehawka, but at a point three miles south, this rate is greater, due to the fact that a southward plunge of more than 100 feet per mile, possibly as much as 5 degrees locally, takes place.

For five miles north of Nehawka the strata are nearly horizontal (in a north-south line), but beyond this point a slight northerly dip is noticeable (about 5 feet to 8 feet per mile). Beyond the Platte River this increases, as shown by drill records at Omaha.

The main line of sharp easterly dips follows very closely to the 96th Meridian from the Kansas line to Nehawka, in Cass County, but apparently divides north of Nehawka and a line of low reverse deviates somewhat to the east and passes near Oreapolis on the Platte River, while another line of folding, having more the appearance of a terrace, is to be found about twelve miles west of Oreapolis, at Cedar Creek.

The exact nature of the structure at Cedar Creek cannot be definitely determined on account of deposits of drift and Dakota sandstone.

The summary of data collected in Nebraska undoubtedly points to the existence of the granite ridge as far north as the Platte River, but the thickness of overlying sedimentaries in the northern limits of the ridge is conjectural. If the ridge continued to rise northward at the rate of 15 feet per mile, which is the rate it rises across Kansas, there would be a granite hill at the Platte River over 700 feet high, or at least a large area of granite to be found under the glacial drift. A well drilled ten miles east of Nehawka, about seven years ago, was abandoned at a depth below 1,000 feet and no granite was encountered. This well was located on a pronounced east-west anticline, which opens to the west at the rate of 20 feet per mile and makes the cross-fold which causes the "high" near Weeping Water.

At Nehawka the rate of easterly dip is 50 feet per mile. At Dubois, where the granite is only 550 feet below the surface, the easterly dip is as high as 170 feet for a mile, with local dips of 5 degrees for over a thousand feet in many places along the Pawnee-Richardson county line.

No easterly dip of this degree can be found in Cass County, but southerly dips into the Nemaha syncline are nearly as steep.

This lessening of the easterly dip may be taken as an indication of a more rounded topography in the Nemaha Mountains and, also, a greater thickness of sediments overlying them than is to be found in the areas in Kansas where sharp easterly dip is usually indicative of shallow granite.

Prospecting for oil should be carried on only after a careful consideration of the location of the "Ridge" and the possibilities of finding a reservoir.

It is known that only thin, fine, sands occur in the lower part of the Pennsylvanian series, in northern Kansas and Nebraska, and a well should be located west of the crest of the ridge so as to take advantage of drainage area and in such a position as to drill the maximum thickness of sediments.

The paucity of sands is somewhat offset by the probability of encountering, at various horizons, conglomerates which originated from the exposed parts of the ridge farther east.

GLEN M. RUBY.

REVIEWS

The Mutue Fides-Stavoren Tin Fields. By Percy A. Wagner. Union of South Africa Geological Survey Memoir No. 16, 1921. 192 pp., 31 plates (including a geological map), 27 text figs.

The interest of this area for the economic geologist lies in its pipes and related replacement deposits carrying tin, tungsten, molybdenum, copper and arsenic, and the problems connected with the replacement of the country rocks.

The rocks are mainly granites and in them are most of the ore deposits. Lower Waterberg volcanic rocks and fragmental sediments, with less quartzite of the Pretoria series, occupy most of the southwestern quarter of the area. The maximum difference in the relief is about 1,000 feet, with small rugged hills in the granitic areas, many of which owe their resistance to large quartz veins. The highest elevation above sea-level given is 3,650 feet. The main features of the topography are thought to be very old and to have been in existence in pre-Karoo times.

Some of the quartz veins in the granite hills are immense. One is said to be 450 feet in width, though just which dimension is meant is not quite clear. Wagner accepts Taber's idea that the force of crystallization of the quartz pushes the rocks apart and thus makes room for the vein. Near one of the veins the granophyre has been sericitized beyond recognition through many feet.

The granitic rocks he divides thus: "1. Red granite (at bottom); 2. Red granophyric granite; 3. Granophyre; 4. A narrow zone of medium-grained granitic rocks occurring at a few places; 5. Intrusions of granite porphyry in the granite; 6. Variously shaped bodies of pegmatite in classes 1–3."

The granite in its upper part begins to carry micropegmatite and thus forms the granophyric granite. Above this, forming, he thinks, a sheet, in some places overlain by granite, is a rock of which the bulk is micropegmatite, and this is the granophyre. It contains some green biotite and black hornblende and Wagner believes it to be a somewhat later sheet-like intrusion.

The granite contains many inclusions of the country rock but Wagner is not a devotee of "simple geology," so that they are all "xenoliths."

Similarly German terms creep in in various places. Areas are described as of so many "morgen" in extent; this means little to most readers outside of South Africa.

There are some aplite and granite-porphyry dikes, and numerous pegmatites. The pegmatites are classed as "any coarse-grained aggregation of feldspar and quartz, or of feldspar alone or quartz alone"—a definition probably not wholly acceptable to all careful geologists. The pegmatites are extremely irregular in form—branching, round, or ovoid—"eyes."

Wagner attempts to explain these irregular forms by supposing that they have filled contraction cavities in the granitic rocks, and that the eyes are "segregation pegmatites." In the vicinity of the tin deposits, and these apparently include most of the pegmatites, the granites are greatly sericitized and greisenized.

The deposits carrying the metallic minerals are mostly in pipes and "eyes." These deposits Wagner shows to be connected with joints and to be located especially at their intersections. The pipes are extremely irregular in shape, size, direction of dip and mineral content. In many ways they are like the scheelite-bismuth-copper bearing pipes of the Deep Creek Mountains, Utah, and the Bolivian replacement tin deposits in granite. They also remind one of the descriptions of the pipes in Queensland and New South Wales.

The pipes generally are in the pegmatites, which they replace. The "eyes" apparently grade into the ordinary pegmatite "eyes." They commonly have a zonal structure with an outer zone of red feldspar, within that a zone of quartz, and in many, a center of fluorspar or calcite, some with ankerite, with or without various ore minerals. Some carry tourmaline with a blue core and dirty brown crust. This blue color in tourmaline has long been considered a sign that the tourmaline is a replacement mineral and in my own experience this has held true. Calcite and fluorspar are almost if not wholly unknown in intrusive pegmatite, but are common in replacement "pegmatites." The pipes are very similar to the "eyes" except as to size and shape.

In the pipes with the tin there is considerable sericite and, especially around the borders of the pipes, an unusual black mica (raven mica) carrying some lithium and altering to chlorite. Other minerals of the pipes are tourmaline; fluor-apatite; chlorite; fluorspar; calcite; ankerite; cassiterite; quartz; specularite; molybdenite; scheelite; wolframite; arsenopyrite; chalcopyrite; bismuth; bismuthinite; galeno-bismutite; galena; pyrite and secondary minerals.

Wagner is an almost meticulously careful observer and has that gift of imagination which is almost a pre-requisite to scientific work. In

many of his deductions, however, it is difficult if not impossible to follow him. Replacement is the keynote in the story of these deposits, but when he finds cassiterite replacing the quartz more readily than the feldspar (p. 74) of granite, it is so contrary to experience in other fields that one hesitates at free acceptance. This hesitation is increased when he finds cassiterite enclosed, or partly enclosed, in quartz crystals explained as replacement of the quartz (p. 76). Incidentally, secondary scheelite formed from wolframite (pp. 74 et al.) is to me very doubtful in spite of the authorities quoted, and the microphotographs (pl. 19) of the replacement of wolframite by scheelite are not wholly convincing in the light of a considerable study of the subject. Scheelite commonly is formed in small quantity (particularly toward the end of mineralization), in wolframite deposits and forms intergrowths with, and fills cracks in, wolframite. Chalcopyrite replacing quartz (p. 127) along successive lines of growth seems to be more readily explained by deposition of the chalcopyrite between the periods of quartz deposition. The replacement of cassiterite by wolframite (p. 91) and of "pegmatitic quartz" by scheelite (p. 139) are also difficult to understand.

Many pipes are partly or wholly hollow, and these cavities Wagner describes as contraction cavities, but they seem much more likely to be solution cavities. The larger number of the pipes are in pegmatites and it seems probable from their irregularity that they (the pegmatites) like the feldspar in the "eyes," are replacements of the country rock made by the same solutions that later dissolved them in turn and replaced them by other minerals. Wagner does not clearly recognize the pipes as replacement phenomena, nor their relationship to the "eyes" for on p. 119 he says of the *"new 'B2' working"*: "Though generally referred to as a pipe, it is not a pipe at all, but consists of a number of superimposed replacement bodies in irregular bodies and eyes of pegmatite aligned along a vertical fissure." The largest pipe mentioned is elliptical, 50 feet across on the longer axis and 35 feet on the shorter. Most of the pipes are very much smaller. They have been followed to depths of only a little more than 100 feet.

There are some replacement deposits in quartzite, and these contain large quantities of specularite. Only one of the deposits is pipe shaped. No arsenopyrite is found in the quartzite. This, however, must be merely one of the vagaries of deposition. In Bajaderia Valle, about 15 miles northwest of Quimsa Cruz (Tres Cruces) Pass, Bolivia, there is a large quantity of arsenopyrite in the tin deposits which are there also replacement bodies in quartzite.

The mineral output to the end of 1920 is valued at more than £190,000.

including 1,313 short tons of tin concentrates, 30 tons of scheelite concentrates, 110 tons of copper ore, 8 tons of white arsenic and several tons of molybdenum concentrates.

FRANK L. HESS.

Who's Who in Engineering. A Biographical Dictionary of Contemporaries, 1922–1923. By JOHN WILLIAM LEONARD. 1509 pp. John W. Leonard Corporation, Brooklyn. $10.00.

The "Who's Who" principle applied to the field of engineering has resulted in this volume, which contains the biographical records of 10,494 engineers in America and foreign countries. The book is well arranged, so that names and addresses may be looked up with a minimum of effort; the many abbreviations are explained in a table at the front of the book. The geographical index in the back should prove a valuable reference feature. The printing and binding are adequate for the purpose.

Every effort has been made to include the names of all engineers of ability and achievement, although many additions will doubtless be made in the second edition. The addresses adjacent to the names enable the book to be readily utilized for a directory as well as a "Who's Who." The biographies are clear and concise, and contain sufficient personal and professional information to make a convenient and valuable reference book.

A. A. BEECHER.

The Bureau of Mines—Its History, Activities and Organization. By FRED WILBUR POWELL. Service Monographs of the United States Government, No. 3. 162 pp. D. Appleton & Company, New York. 1922.

This is one of a series of monographs prepared by the Institute for Government Research, to give a detailed description of the various services of the government. The purpose of the series is to present in as simple a form as possible the history, functions, and organization of each service, the laws governing its operations, and financial statements showing its appropriations and expenditures, to be used by administrative and legislative officials as a basis for intelligent action. They are also intended to enlighten public opinion through definite knowledge of the organization and operations of the government.

The monograph dealing with the Bureau of Mines is prepared according to the uniform plan. The first chapter gives the history of its creation and development; the second chapter describes the activities of the Bureau, under the headings "Promotion of Safety and Health," "In-

vestigation of Mine Hazards," "Technological Researches and Investigations," "Administration," "Compilation of Mining Laws and Regulations," and "War Activities." The third chapter covers briefly the organization, supplemented by an outline in the appendix. The appendix, which is over twice as long as the main part of the book, includes a full statement of the laws and regulations dealing with the Bureau of Mines, statements showing appropriations, receipts, and expeditures for a period of years, descriptions of publications, plant, and equipment, and a bibliography. The book is well printed and fairly well bound.

It is purely a descriptive and not a critical study. To those interested it will be a convenient and accurate source of information.

A. A. BEECHER.

SOCIETY OF ECONOMIC GEOLOGISTS

As a result of the recent ballot the following officers for the Society have been elected for 1923:

J. E. Spurr, President
Andrew C. Lawson, Vice-President
Ralph Arnold
L. C. Graton } Councilors—Term, 2 years
Willet G. Miller

The Council announces the election to membership of Mr. Guy Norman Bjorge.

The Society held its annual meeting at Ann Arbor, Michigan, December 28 to 30, jointly with the Geological Society of America. The meeting was highly successful and the attendance at the technical sessions was large. In addition to joint sessions with the Geological Society of America on the Copper Deposits of the Lake Superior Region and on Mountain Building, some twenty other papers were read or presented by title. Unfortunately, the lack of time limited the opportunity for a healthy amount of discussion. The retiring President's address, delivered by Mr. Waldemar Lindgren, was entitled: Concentration and Circulation of the Elements from the Standpoint of Economic Geology.

The members participated in the Annual Banquet and Smoker of the Geological Society of America and the Arrangements Committee organized a separate luncheon for the members of the Society only.

The membership is deeply indebted to Professor C. W. Cook of the University of Michigan, Professor W. S. Bayley, Chairman, and Messrs. DeWolf, Grant, and Grout of the Arrangements Committee, and Mr. B. S. Butler, Chairman of the Program Committee, for the success of the meeting.

The Society will hold a meeting in May in New York, at some date to be announced later. There will be presentation and discussion of papers on applied geology and the presidential address; also a dinner. The Society will also officially coöperate with the Geological Society of America in the meeting of the latter in December 1923, at which date the final annual business meeting of the Society of Economic Geologists will be held as usual.

Professor Alan M. Bateman of Yale University, New Haven, Conn., is chairman of the committee on papers for the meeting. Will those who plan to submit papers for this meeting please advise him as soon as possible.

SCIENTIFIC NOTES AND NEWS

R. A. F. Penrose, Jr., has been elected to succeed Dr. John Cadwalader as president of the Academy of Natural Sciences.

Waldemar Lindgren addressed the Geological Club of Yale University on January 25 on the Geology of Bolivia.

E. F. Burchard has arrived in the United States from Buenos Aires.

J. W. Gregory has returned to Glasgow from South China, and has been awarded the gold medal of the Royal Scottish Geographical Society.

Sidney Paige, of the U. S. Geological Survey, was a recent visitor in New Haven.

R. R. Thompson has been appointed professor of petroleum engineering in the Birmingham University.

N. H. Darton of the U. S. Geological Survey returned to Washington in December after extended field work in Arizona, completing the geologic map of Arizona for the State Bureau of Mines. The University of Arizona has conferred on him the honorary degree of Doctor of Science in recognition of his geological investigations in the west.

Leon Feuchere, formerly with the Copper Queen Consolidated Copper Company, is now undertaking leasing on his own account in Bisbee, Arizona.

S. R. Capps and T. B. Pendleton have returned to New York from the Near East.

Arthur Notman, who has been associated with the Phelps Dodge mines for fourteen years, has resigned as mine superintendent of the Copper Queen Mine, and has left for New York, where he will be associated with James R. Finlay in geological and mine consultation work.

Harry Hays, previously chief geologist for the Detroit Copper Company at Morenci, Arizona, and later in the office of P. G. Becket, has been appointed to succeed Mr. Notman.

G. F. Loughlin, head of the mineral resources division of the U. S. Geological Survey, has been appointed secretary of a committee to consider ways of improving the arsenic situation.

C. W. Purington has returned from Yokohama, and is now in Boston.

E. L. Ickes, who has been connected with the geological departments of the Mexican Eagle Oil Company, Pearson & Son of London, and the Standard of California, has opened an office in the Title Insurance Building, Los Angeles, where he will specialize in geological investigations in petroleum.

J. A. Burgess has completed several mine inspections near Rochester and Winnemucca, Nevada, and has returned to Berkeley, California.

The United States Geological Survey was represented by over 20 members at the annual meetings of the Geological Society of America and its affiliated societies.

The Geological Society of America and its affiliated societies held their annual meeting at the University of Michigan, Ann Arbor, Michigan, December 28–30. The meeting was unusually successful from the standpoint of attendance, character and diversity of the papers, and the convenience of the University of Michigan buildings, particularly the University Union for a headquarters. The local committee, under the leadership of Professor Hunt, are to be congratulated for their careful arrangements. Dr. David T. White was elected President and Charles P. Berkey Secretary of the Society for the ensuing year. The December, 1923, meeting is scheduled to take place in Washington, D. C.

The Society of Economic Geologists held its annual meeting jointly with the Geological Society of America.

R. Gilman Brown has been elected President of the Institution of Mining and Metallurgy.

Washington University, St. Louis, has received a gift of $250,000 for a building for the use of the geology department. The building is the gift of Mrs. Newton R. Wilson as a memorial to her husband.

The *Monthly Bulletin* of the Canadian Mining Institute, commencing with the February issue, will include also the *Transactions* of the Institute, and the sending out free of charge of the bound annual volume will be discontinued.

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